1-1-2008

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Recommended Citation

Shelton, Mona C., "The use of reciprocal interdependencies management (RIM) to support decision making during early stages design" (2008). *Theses and Dissertations*. 4689.
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THE USE OF RECIPROCAL INTERDEPENDENCIES MANAGEMENT (RIM) TO SUPPORT DECISION MAKING DURING EARLY STAGES DESIGN

By

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A Dissertation
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy
in Engineering
in the Department of Industrial and Systems Engineering

Mississippi State, Mississippi

May 2008

THE USE OF RECIPROCAL INTERDEPENDENCIES MANAGEMENT (RIM) TO SUPPORT DECIION MAKING DURING EARLY STAGES OF DESIGN

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Title of Study: THE USE OF RECIPROCAL INTERDEPENDENCIES
MANAGEMENT (RIM) TO SUPPORT DECISION
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Pages in Study: 466

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Published works cite that 70-80% of the total cost of a product is established during conceptual design, and that improvements in time-to-market, quality, affordability, and global competitiveness require the development of better approaches to assist decision-making during the early stages of product design, as well as facilitate enterprise knowledge management and reuse.

For many years, concurrent engineering and teaming have been viewed as “the answer” to product development woes, but studies reveal teaming is not sufficient to handle the task complexities of product development and the long-term goal of enterprise learning. The work of Roberto Verganti (1997) provides new insights with regard to reciprocal interdependencies (RIs), feedforward planning, selective anticipation in the context of improving teaming and concurrent engineering, as well as enterprise learning, knowledge management, reuse.

In this research, reciprocal interdependencies management (RIM) is offered as a means of addressing product development and concurrent engineering issues occurring in the early stages of design. RIM is a combination of Verganti’s concepts, a conceptual RIs structure, new RIM-application strategies, RIM-diagramming, and a conceptual RIM-based decisions support system, which come together to form a vision of a RIM-based enterprise knowledge management system. The conceptual RIM-based DSS is presented using the specific case of supporting a working-level integrated product team (IPT) engaged in the design of an aircraft bulkhead. A qualitative assessment tool is used to compare RIM to other approaches in the literature, and initial results are very favorable.

Keywords: conceptual design, reciprocal interdependencies management, RIM, reciprocal interdependencies, feedforward planning, selective anticipation, superficial anticipation, feature-based design, feature-based cost, aircraft cost analysis, IPT, integrated product team, working-level IPT, decision support systems, enterprise learning, enterprise knowledge systems, early process engineering, preplanning knowledge

DEDICATION

This research is dedicated to my family, for without their love, support, and sacrifice, none of it would have been possible. To my mother and father, Janice and Taulbee Carty, for instilling in me the value of education, and my mother especially, for her love of learning. To my brother Gary and his wife, Kathy, for their encouragement. To my stepson, Gregory Shelton, and his wife, Jessica, for keeping me in their thoughts and prayers. To my children, Afton and Geordan Strain, for encouraging me to study even when it sometimes meant that they missed out on my attention. To my husband, Robert Shelton, who has sacrificed many weekends, summer vacations, and holidays in support of my educational pursuits. Without his support, love, and encouragement, none of which would have been possible.

ACKNOWLEDGMENTS

I would like to express my sincere appreciation to my major professor, Dr. Allen Greenwood, for his encouragement and guidance throughout this process. Dr. Greenwood has been an outstanding professor, and the knowledge gained from his courses, as well as his publications, have proven to be invaluable to this research effort. He has spent countless hours wading through many first draft pages, and without his contribution and guidance, this research effort would not have been possible.

It has been said that first impressions are lasting ones, and the Department of Industrial and Systems Engineering could not have a better ambassador to potential graduate students than Dr. Stanley Bullington. In his role as graduate coordinator, he was the first person that I spoke with regarding the PhD program as Mississippi State University, and the way in which he treated me during my initial inquiries played a major role in my decision to pursue graduate education at MSU. My sincere thanks to Dr. Bullington for helping me choose the right graduate school, being a great professor, and graciously serving on my committee.

My sincere gratitude is extended to Dr. John M. Usher for being one of the best professors that I have had in my academic career, a role model for organization and hard work, and serving on my committee. His book, <u>Integrated Product and Process</u>

Development: Methods, Tools, and Technologies," made lasting impression on me, and contributed significantly to the vision for this research.

Special thanks to Dr. Masoud Rais-Rohani from the Department of Aerospace Engineering for serving on my committee, and providing me with invaluable research assistance. His though-provoking questions related to the research topic challenged me and added depth to my understanding. Dr. Rais-Rohani's writings, and those he inspired by Dr. Peter Chapman, which were extremely beneficial in the realm of conceptual aircraft design.

Thanks to Dennis Mohr for the contributions he made to my knowledge during our time together at MSU and for being my friend, and also to Rusty Foster for his unwavering support of distance education and the personal touch he added to all aspects of his job in support of distance students. In addition, I am forever grateful for the unwavering friendship and support of Sheila McClung as well as the many mentors and integrated product team members who have contributed to my professional life.

Finally, I would like to thank the Department of Industrial and Systems Engineering at Mississippi State University for providing me with the opportunity to pursue graduate education. In particular, for making so many courses available at a distance to accommodate working adults.

TABLE OF CONTENTS

APPENDIX

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

There is a well-identified need in literature to develop frameworks, methodologies, and systems that have the potential to extend knowledge with regard to enterprise decision making during the conceptual design phase of the product development process. The majority of published works related to product development assert that between 70-80% of the total cost of a product is established during the conceptual design phase (Fabrycky and Blanchard, 1991; Feng and Song, 2000; Lee and Kelce, 2003; Park et al., 2002; Shehab and Abdalla, 2001; Wang and Wang, 2002). Likewise, improvements in conceptual design decision making are also linked to needed enterprise improvements in time-to-market, quality, affordability, and global competitiveness (Feng and Song, 2000; Greenwood and Ormon, 2004; Liebl and Hoehne, 1999; Rehmann and Guenov, 1998; Yang et al., 2003).

In order to improve conceptual design phase activities, the decision-drivers of downstream activities need to be conveyed systematically to the earliest decision makers in business management, engineering, and manufacturing. Enterprise knowledge and learning need to be captured and formalized for reuse in order to improve conceptual design decision making. (Allada and Agarwal, 1996; Hsu and Woon, 1998; Lee et al., 2001; Ma et al., 2002; Reich et al., 1999; Richards, 2000; Xiong, 2003; Yang et al., 2003).

Though much is understood about what needs to be done, the elusive question is "How?" How does an enterprise go about improving early design stage decision making strategies and tools?

Since the late 1980s, the question of "how" has been addressed within the context of concurrent engineering, teaming, and a wide array of decision making tools intended to improve the product development process. However, a review of the literature indicates that many of the product development improvement obstacles identified in the 1980s as the justification for concurrent engineering still exist today and concurrent engineering efforts are not uniformly successful. (Verganti, 1998, chapter 11; Appendix A.)

In the book chapter titled "Anticipating Manufacturing Constraints and Opportunities in the Concept Generation and Product Planning Phases," Roberto Verganti (1998, chapter 11) addresses the elusive question of "how" in an in-depth study that involves a literature review and a survey of 12 companies that utilize teaming and concurrent engineering in the automobile, helicopter, and white-goods (small appliances) industries. The results of Verganti's work offer insights into why some companies are successful in utilizing concurrent engineering to anticipate manufacturing constraints and opportunities during conceptual design, why others are not successful, and offers concepts to improve product development decision making strategies and tools.

The results of Verganti's study provide several new insights that have relevance to improving product development endeavors. Verganti reports that even though many tools had been proposed in the literature, they lack insight into the complex mutual interactions that take place in conceptual design decision making. Further, he asserts that the empirical validation of these tools and their effectiveness is often overlooked.

Verganti's study also discusses relevant survey results in the context of reciprocal interdependencies management (RIM), feedforward planning, and relevant factors in order to explain key components of successful and unsuccessful concurrent engineering conceptual design efforts. The concepts and factors Verganti discusses directly or indirectly (to be discussed more in-depth in Section 1.3) in this research are:

- Reciprocal interdependencies management (RIM)
    - Feedforward planning
    - Selective anticipation
    - Commonality
- Factors affecting and measurements of successful RIM
    - Superficial anticipation
    - Early process engineering
    - Preplanning knowledge
    - Feedforward planning effectiveness

However, it should be noted that Verganti never uses the phrase reciprocal interdependencies management or RIM. Instead, he discusses various concepts that are implied to deal with their management.

Verganti acknowledges task complexities involved in the identification of reciprocal interdependencies and the use of feedforward planning efforts to manage them is usually hindered by a lack of well-structured methods and the amounts of information involved. In addition, teaming is not sufficient to handle the management of reciprocal interdependencies.

Another problem of product development teaming efforts noted by Verganti is that the efforts of the pre-project team, or earliest decision makers, is not documented in a manner that is meaningful to later teams. Hence, there is limited opportunity for systemic learning. The enterprise cannot recreate how the increase in product development knowledge leads to a new decision.

The majority of Verganti's discussions and recommendations remain at a high-level, and the work eventually focuses on broader recommendations dealing with feedforward planning, such as systemic knowledge, knowledge reuse, communication, harmonized objectives, supported proactive thinking, and planned flexibility. However, for individuals with integrated product team (IPT) experience and associated knowledge of task complexities and approaches used in industry, Verganti's work provides many avenues from which to expand upon or further refine within the context of conceptual design decision making. Verganti's research offers an effective springboard to further investigate the question - "How does an enterprise go about improving early design stage decision making strategies and tools?"

The remainder of this chapter is organized as follows:

- Identification of problems and needs
    - Obstacles to development process (PDP) improvement
        - Sequential task completion and information interchange
        - Product development decision making processes are not formalized
        - Early product development decision making information is not linked to downstream activities
        - Product development decision making information guarded by cultural and behavioral issues
        - Enterprise information systems do not support knowledge reuse during early product development
    - Concurrent engineering problems and lack of success
        - Poor management of communication linkages and complexities

        - Specialized hierarchies of knowledge
        - Cultural aversion to detailed and methodical thinking
        - Cultural bureaucracy and systemic complexity
- Initial list of research considerations (based on problems/needs) and next steps
- An executive summary of Verganti’s research
    - Definitions of reciprocal interdependencies
    - Reciprocal interdependencies management (RIM)
        - Feedback planning versus feedforward planning
        - Selective anticipation
        - Commonality
    - Factors affecting/indicating successful RIM
        - Superficial anticipation
        - Early process engineering
        - Preplanning knowledge
        - Feedforward planning effectiveness
- Feedforward planning knowledge management issues
    - Knowledge management strategy is inhibited by enterprise culture
    - IPT knowledge management prior to design release is dependent upon personalization
    - Functional knowledge management after design release is not codified for reuse
    - Knowledge management strategy does not fully utilize selective anticipation and commonality opportunities
- Research objectives
- Scope of the research
- Research limitations
- Dissertation roadmap

1.1 Identification of Problems and Needs

In order to address the basic question of “How does an enterprise go about improving early design stage decision making strategies and tools?” - it is necessary to begin by identifying and categorizing pertinent problems and needs at a high-level. In the next two sections, obstacles to product development process improvement and concurrent engineering are discussed and relevant research issues are identified.

1.1.1 Obstacles to Product Development Process Improvement

The obstacles that stand in the way of improving the product development process have been a topic covered in research for a very long time, and they are well represented in the literature. One of the contributions of this research is to collect and distill into prioritized categories the many different obstacles identified in the literature. The prioritization is based not only on the number of occurrences in the literature, but also on this author's work experience.

This research highlights the fact that a significant number of the problems discussed many years ago still exist today. For example even after 20 years of concurrent engineering teachings, sequential task completion and information exchange are still noteworthy problems for a significant number of enterprises.

The literature identifies a variety of obstacles to product development process improvements within a manufacturing enterprise. The sections that follow discuss these categories of predominant recurring themes:

- Sequential task completion and information exchange
- Product development decision making processes are not formalized
- Early product development decision making information is not linked to downstream activities that occur after engineering design release
- Product development decision making information is guarded by cultural and behavioral issues
- Enterprise information systems do not support knowledge reuse during early product development

1.1.1.1 Sequential Task Completion and Information Exchange

Most enterprises are made up of organizations, job descriptions, information systems, procedures, problem-solving approaches, etc. that were originally created based upon Adam Smith’s division of labor theory. Even though these systems have adapted to incorporate computer technology and new theories, the underlying procedural structures remain intact (Lee and Kelce, 2003; Wierda, 1990). Hence, the collective knowledge of the enterprise is geared toward the completion of specialized tasks in a sequential fashion using complete information supplied from the preceding supplier of information in the process (Boothroyd, 1994; Evans et al., 1998; Ferrelrinha et al., 1993; Tolometti and Saunders, 1998; Shehab and Abdalla, 2001).

The sequential nature of task completion and information interchange is most readily apparent in the activities that take place after engineering design release. The sequential orientation is ideally structured for short-term shop floor control objectives. However, it does not readily support a user’s effort to work with incomplete or varying levels of information availability before design release.

1.1.1.2 Product Development Decision Making Processes are Not Formalized

Most of the product development decision making within an organization is not formalized. The how and why of decision making is usually not documented in enterprise systems, and “lessons learned” are primarily applied on an individual basis. Information related to decision making resides in someone’s desk or brain, and only the results of their efforts are stored in the systems. The formalization of the available information takes place once decisions are made and placed into the system to be used by the next function. This problem has been a primary obstacle in creating many different types of expert systems. (Andersson et al., 1995; Austin et al., 2001; Ou-Yang and Lin, 1997; Park and Khoshnevis, 1993; Xiong, 2003.)

1.1.1.3 Early Product Development Decision Making Information is Not Linked to Downstream Activities

In most cases, information created during early product development is not directly linked to downstream activities that take place after an engineering design is released. Before a design is released to the manufacturing execution system, there is no quick and easy way for a user to develop a "best guess" of the processes, routing, resources requirements, schedule, or potential quality issues related to a design. However, as soon as a design is released, there are automated computer systems, processes, and procedures within the enterprise that exist for the sole purpose of developing these types of information, i.e., manufacturability assessment, process routing, pricing (direct labor hours estimates), and scheduling.

Once a design drawing is released during the detail design phase, a variety of systems are used for shop floor control related tasks, such as the creation of work instructions, capacity requirements planning, etc. However, during the early stages of product development, any decision making related to these tasks is performed using ad hoc or stand-alone approaches that are not fundamentally a part of the enterprise systems that engage after a design is released. Examples include the following:

- Manufacturing standard information is created and formatted to load capacity requirements and cost accounting systems, but it is not directly linked to engineering design or cost assessment systems used by analysts supporting Business Management or Engineering

- Manufacturing process availability and capability data are not systematically linked to design systems used by Engineering
- Process cost and schedule information found in Factory Management systems is not linked to engineering systems

Once a completed design drawing is released, a formalized approach exists to translate the engineering design information for predefined manufacturing execution purposes. This approach is computerized, and has a significant level of automation. Prior to the event of design release, a formalized, computerized (automated) exchange of information between the engineering activity and factory management systems involved in manufacturing execution does not occur. (Brunetti and Golob, 2000; Chen and Jang-Jong, 1999; Chen and Liang, 2000; Lee and Kelce, 2003; Huang et al., 2001; Kimura and Grote, 2002; Kolb and Bailey, 1993; Vollerthun, 1998).

1.1.1.4 Product Development Decision Making Information Guarded by Cultural and Behavioral Issues

Many manufacturing enterprises started and adapted years before automated information systems became so readily available. As one can imagine, in the past, job titles and promotions were often based on one's ability to be the person *in the know*, as well as how effectively functional organizations protected access to information. As computer information systems became mainstream, the cultural view of guarding information played a role in how these systems were used. Quite often, new information systems were structured around traditional organizational theory, as opposed to discovering new ways of doing business that optimized information sharing within the enterprise. In other words, the new software tools were formatted to *old* organizational structures and processes, as opposed to using the capabilities of the software as the basis of creating *new* organizational structures and processes.

In many corporate cultures there is still a general reluctance among personnel to share knowledge, information, and expertise. In particular, when it comes to “tricks of the trade” with regard to working with incomplete information, it is not uncommon for “experts” to assert that their job is just too complex to explain.   These experts resist efforts to computerize/automate significant aspects of their decision making processes. (Asideu and Gu, 1998; Austin et al., 2001; Pratt, 1984; Tolometti and Saunders, 1998; Vollerthun, 1998; Wierda, 1990).

1.1.1.5 Enterprise Information Systems Do Not Support Knowledge Reuse During Early Product Development

Many manufacturing enterprises have information systems that store historical data. The problem is that these organizations do not go a step further to turn data into knowledge and information for reuse. For example, a company’s computer system may hold 50 years of NC (numerical control) machining data for bulkheads. However, in order to extract the data and make comparisons to the current design, one has to be an expert programmer and know, in detail, the changes in department numbers, computer record fields, etc. to get needed information and make sure it is utilized properly. To make matters more complicated, even if someone retrieves the data, there is likely no record as to “why” someone previously selected one process over another, or “why” one bulkhead costs more than another. At that point, a person will likely have to access all of the design drawings and specifications, and try to rationalize the variances. (It is no wonder employees guard this type of information once they go to such trouble to develop it.)

The task of modeling relationships between product design drivers and the process-dependent parameters is a very difficult obstacle for integrated product and process development to overcome. (Rais-Rohani and Greenwood, 1998.) When an organization fails to systematically record the “whys” of decision making, it makes the task of relationship modeling increasingly complex; one that can only be accomplished consistently by a few dedicated experts within an organization.

In the book, The 7 Habits of Highly Effective People, Stephen Covey lists the first two habits as: Rule 1: Be proactive, and Rule 2: Begin with the end in mind. The underlying problem with many enterprise information systems is that they were not designed with the goal of creating enterprise knowledge and the capturing of and reuse of organizational learning. Instead, the data collected are just a byproduct of short-term shop floor control needs. Keeping years of actual data in computer files is not “learning.” (Covey, 1989; Cutosky et al., 1988; Geiger and Dilts, 1984; Haimes and Schneiter, 1996; Hsu and Woon, 1998; Kimura and Grote, 2002; Luby et al., 1986; Ou-Yang and Lin, 1997; Sky and Buchal, 1999; Taleb-Bendiab, 1993; Vollerthun, 1998; Yang et al., 2003.)

The conclusion is reached that the following items need to be considered at a high-level when contemplating strategies and tools to improve conceptual design decision making:

- Concurrent task completion and information interchange
- Product development decision making systems that inhibit negative cultural

and behavioral issues related to information and associated power

- Formalized product development decision making processes that are linked to downstream activities and are a part of a larger enterprise information system that supports reuse

1.1.2 Concurrent Engineering Problems and Lack of Success

Most individuals involved in product development decision making are familiar with concurrent engineering and its envisioned benefits. The following quotes are offered to serve as a basis of discussion.

> Concurrent Engineering is *"a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life-cycle from conception through disposal, including quality, cost, schedule, and user requirements."* (Winner et al., 1988.)
>
> Concurrent Engineering *"offers the potential benefits of reduced development time, the ability to uncover design flaws earlier in the development process, fewer engineering changes, improved quality, increased white collar productivity, and higher return on assets."* (Schultz, 2006.)

Studies and surveys report that most companies utilize concurrent engineering, but that their efforts have not been as successful as anticipated due to a variety of problems. (Constable, 1993; Lawson and Karandikar, 1994; Waterson et al.,1999; Portioli-Staudacher et al., 2003.) Another contribution of this research is to distill the many different concurrent engineering problems identified in the literature into prioritized categories.

Specific issues related to the lack of success are identified as:

- Poor management of communication linkages and complexities
- Specialized hierarchies of knowledge
- Cultural aversion to methodical thinking and outcome control

- Cultural bureaucracy and systemic complexity

The majority of the identified concurrent engineering issues deal with how knowledge links (reciprocal interdependencies – discussed in Section 1.3.1) are managed within an enterprise. These issues are discussed in more detail in the sections that follow. In addition, pertinent relevant conclusions are highlighted.

1.1.2.1 Poor Planning and Management of Communication Linkages and Complexities

Concurrent engineering sounds very promising and the explanation borders on being nearly “common sense.” However, the complexities of the required communication/knowledge linkages are not fully explored in the literature that discusses “Concurrent Engineering.” (What sounds so simple…is not so simple.)

Hoedemaker et al. (1999) demonstrates that limits to the benefits of concurrency exist. As communication linkages within the organization become more complex, the less able concurrency can positively affect development time. In general, the more complex the organization and the project, the stricter the limits to concurrency, and the greater need to understand which decisions are affected by concurrency and which may not be. There are potentially adverse effects to placing too much emphasis on concurrency without fully exploring communication linkages.

Alcatel-Lucent (a global communications solutions provider) has achieved considerable success with concurrent engineering, but also reports that problems exist when the coding process is broken down into too many independent modules. The coding process for large programs for switching systems is attacked by dividing into modules. As the module size becomes smaller, the degree of parallel activity clearly increases. However, at the same time, the inefficiencies increase because of problems created by poor interfacing (poorly defined knowledge links). As the communication burdens increase on individual programmers, the number of avoidable errors increases. (Hoedemaker et al., 1999.)

Constable (1993) discusses how companies in the United Kingdom interpreted cross-functional teaming and simultaneous engineering as being approaches to reduce the need for management planning. The idea being that teaming should be done in an organic manner where management's main role is to provide a mutually supportive environment. This thinking appears to be opposite of what Toyota Corporation, known for its success in concurrent engineering, used on the development of the new Camry where the emphasis was on management planning. (World Car Fans, 2006.)

Patrashkova and McComb (2004) developed a computational model to simulate cross-functional teaming effectiveness in a simultaneous engineering environment and determined that having the entire team involved in every decision was ineffective. Instead, management should establish a framework where only requisite pieces of information required team involvement.

Rickman (2001) reported that having a poorly defined IPT structure was more detrimental to Raytheon in implementing concurrent engineering than not using IPTs at all. The IPTs at Raytheon are tasked with developing technical product requirements plus schedule and cost requirements for the product as well as their own functional deliverables. Few (if any) individuals possessed the knowledge or skills to meet these expectations.

It is inferred from the preceding discussions that the following items should be considered when contemplating strategies and tools to improve product development decision making:

- Definition of the product development process (high-level)
- Definition of the decisions that IPTs are expected to make (lower-level)

1.1.2.2 Specialized Hierarchies of Knowledge

Winter (1999) discusses how specialized hierarchies of knowledge have played a role in the U.S. automakers' ability to capitalize on the benefits of simultaneous engineering in an article titled, "Back to the Future? – Simultaneous Engineering." During the prolonged period of industrial growth in the 1960s, 1970s, and 1980s, many companies moved toward Adam Smith's theory of organization, and workers were organized by specialty. Government regulation also dramatically increased during this same time period, and this also added to automakers' decisions to create highly specialized hierarchies. Specific groups were formed inside corporations to coincide with particular regulatory legislation. (Winter, 1999.)

During the same period of time, Japan went through hard times, and had to become more efficient. Japanese automakers required staffs that were considered jacks-of-all-trades. (Winter, 1999). Ironically, the jacks-of-all-trades approach was historically the philosophy in the U.S. prior to the 1960s and Adam Smith's theory of organization by specialty. Hence, this author implies that in order to solve some of their problems, companies are going to have to go "back to the past" and find, or train, employees and create systems that support more than one-dimensional, specialized problem-solving.

It is inferred from the preceding discussion that there are knowledge gaps that exist with regard to how knowledge is linked within an enterprise. Effective strategies and tools used in conceptual design decision making need to identify existing hierarchies, drawing information from these hierarchies, and convey it in a manner that meets many different aspects of decision making concurrently. Further, the strategies and tools need to facilitate multi-dimensional thinking.

The list of items/needs provided in earlier sections expands as follows:

- Definition of the product development process (at a high-level)
- Definition of the decisions the IPTs are expected to make (at a low-level/working-level)
- Specialized hierarchies/systems require restructuring for other uses (at a low-level of detail)

1.1.2.3 Cultural Aversion to Methodical Problem Solving and Outcome Control

The typical IPT is composed of individuals with engineering degrees, individuals with degrees in other disciplines, and individuals with no college degree. In general, individuals who have not been trained in methodical thinking tend to resist systematically solving issues, and more often than not, make decisions using their "feelings" or the desire for consensus. If everyone's opinion is not validated, regardless of the level of substantiation, it becomes a real problem. Dana L. Hargitt is an executive at Toyota who worked 20 years at General Motors (GM) prior to joining Toyota in 1996. When asked about concurrent engineering at GM, she said, … "Too often, concurrent engineering meetings turn into coffee klatches and lack a systematic approach to problem solving."

(Vasilash, 2001.) This assertion is also supported by this author's work experience in IPTs.

Miller and Guimaraes (2005) discuss that one of the problems with cross-functional teaming is how it is managed. There are two types of control: behavioral and outcome. Behavioral control deals with how a task is accomplished, and outcome control deals with the results of the task. Effective cross-functional teaming required both types of controls, but the emphasis at many companies has been very heavily weighted on the behavioral aspects of control, such as teamwork, communication, support, consensus, diversity, and validation.

It is inferred from the preceding discussions that in order for an individual to be effective as an IPT member, he/she requires: 1) extensive training in multi-dimensional thinking and how to work with incomplete information, 2) systems and tools to "lead them through" the required decision making process, or 3) some combination of both.

The list of items/needs provided in earlier sections expands as follows:

- Definition of the product development process
- Definition of the decisions the IPTs are expected to make
- Specialized hierarchies require restructuring and/or reformatting for other uses
- IPT members require systems and tools that "cue them" as to which decisions need to be made and provide information in a format to assist with the decisions (i.e., decision support systems)

1.1.2.4 Cultural Bureaucracy and Systemic Complexity

For some companies bureaucracy and complexity are built into the very fabric of their culture. For example, the defense industry has many oversight agencies involved in the defense acquisition process, and its approach to doing business grew up in the era of cost plus contracting. Hence, unnecessary complexity and paper trails are part of the culture. It is going to be very difficult to make radical changes as long as the primary customer and "manager" of the acquisition process is the government. (Ingols and Brem, 1998.) Similarly, automakers routinely have considerable management involvement in routine decisions and a great deal of government agency oversight. In general, individuals and enterprises resist changing roles and responsibilities and performing management functions differently. (Winter, 1999.)

The conclusion is reached that even the "best ideas" for improving product development decision making systems and tools may not be fully implemented because of the information-power that some organizations and individuals would have to relinquish to implement detailed decision support systems.

1.2 Initial List of Research Considerations and Next Steps

Based on the consideration of product development decision making obstacles and concurrent engineering problems, the following list of research considerations emerges:

- Definition of the product development process
- Definition of the decisions the IPTs are expected to make
- Specialized hierarchies require restructuring and/or reformatting for other uses
- IPT members require systems and tools that “cue” them on which decisions need to be made and provide information in a format to assist with the decisions
- Concurrent task completion and information interchange
- Product development decision making systems that inhibit negative cultural and behavioral issues related to information and associated power
- Formalized product development decision making processes that are linked to downstream activities and are a part of a larger enterprise information system that supports reuse

One research consideration identified is the *need for a better defined product development process*. Two other research considerations that come to the forefront are *the need to better define IPT decisions* and *the need to develop integrated decision support systems for use by IPTs.*

In order to improve the product development process, it makes sense that one must first define it. However, a generic product development process was not readily available in the literature. Hence, one of the first tasks associated with this research is to develop a generic product development process. Further rationale behind the need for a generic product development process and a series of IDEF0 (Integration Definition for Function Modeling) diagrams are presented in Chapter 2.

The literature review effort located hundreds of different approaches that are dedicated to improving early product development decision making. Once the need for a generic product development process was identified, it seemed logical to go back and reorganize the literature using the activities on the diagram.

As discussed in the literature review in Chapter 3, the effort ultimately indicates that the most promising works in the realm of product development process improvement, concurrent engineering, and conceptual design decision making are those that emphasize the systematic integration of multiple product development activities and related decision making, with an emphasis on structured knowledge reuse. From among the promising works, the approaches of Roberto Verganti (1998, chapter 11) are selected for further study. (Verganti's work is published in a book co-edited by Dr. John Usher, titled "Integrated Product and Process Development: Methods, Tools, and Technologies.) In the next section, Verganti's research is discussed.

1.3 An Executive Summary of Verganti's Research

Roberto Verganti performed a survey of 12 companies operating in the automobile, helicopter, and white goods (small appliances) industries involved in new product development using concurrent engineering and teaming. Based on the results of this research, Verganti offers explanations as to why some companies are successful at teaming, concurrent engineering, and the systematic anticipation of manufacturing constraints and opportunities during conceptual design while other are not. In addition, he offers insights as to why the majority of published works fall short with regard to addressing the real needs of teams and early decision makers. The key concepts that Verganti discusses (either directly or indirectly) are as follows:

- Reciprocal interdependencies management (RIM)
- Feedforward planning
    - Selective anticipation
    - Commonality

- Factors affecting and measurements of successful RIM
    - Superficial anticipation
    - Early process engineering
    - Preplanning knowledge
    - Feedforward planning effectiveness

Verganti's concepts deal with decision making and how knowledge is created and exchanged among activities and teams to make decisions. The relevance of Verganti's assertions to other industries or the application potential of his concepts may not be immediately "seen" or understood by individuals who have not been involved in the product development process or have not been a member of an IPT. Hence, this author's professional work experience played a role in selecting this avenue for further research. Many of the problems Verganti identifies in his research are those that this author has experienced in the workplace, and similarly, the concepts for improving decision making ring true. In the sections that follow, each of Verganti's concepts is discussed.

1.3.1 Definitions of Reciprocal Interdependencies

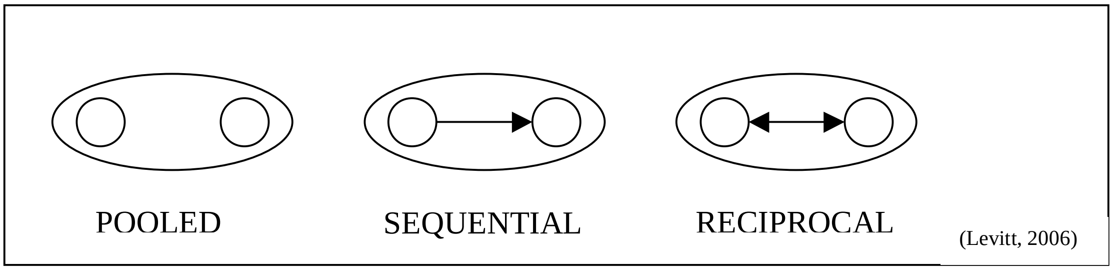
Before discussing the *management* of reciprocal interdependences, it is first appropriate to discuss some definitions of *reciprocal interdependencies* (RI) found in the literature. Definitions of RI vary in the literature, and until very recently, were not widely applied. When this research began, there was little relevant discussion of RI within the context of the product development process other than Verganti's work from

1998. Before presenting Verganti's definition of RI and his ideas for managing them, two other definitions of reciprocal interdependencies used in the literature are offered, which include illustrations and an expanded context of use. These two definitions are used in the context of supply chain management improvement.

Levitt (2006) defines three types of work accomplished in a supply chain as follows:

- Pooled work: work accomplished dependent of other workers
- Sequential work: work accomplished once others have completed specified work
- Reciprocal work: work accomplished in cooperation or collaboration with other work through a series of "mutual adjustments"

Levitt offers the following illustration related to work accomplishment interdependencies:

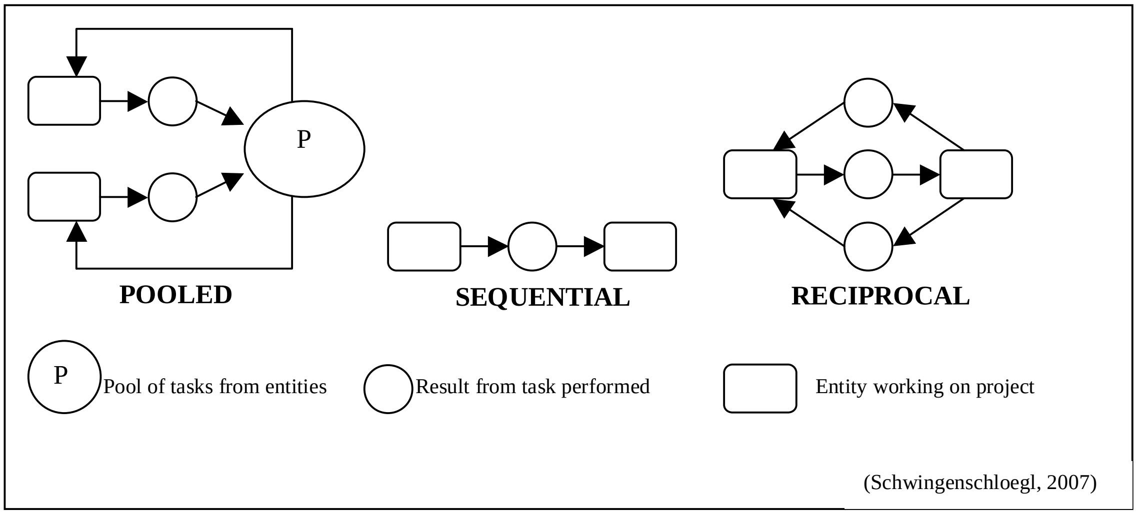


(Levitt, 2006)

Figure 1.1 Types of Work Accomplishment Interdependencies

Levitt asserts that most reciprocal work is accomplished via meetings, but would benefit from collaborative design processes and supporting tools. Further, some work that is accomplished sequentially would be better accomplished using a reciprocal approach. Though not explicitly stated by Levitt, it can be asserted that reciprocal interdependencies management approaches are needed to facilitate supply chain management.

Schwingenschloegl (2007) provides a classification of task interdependencies within the context of supply chain modeling and simulation in the illustration that follows:



(Schwingenschloegl, 2007)

Figure 1.2 Types of Task Accomplishment Interdependencies

Schwingenschloegl's wording and pictorial interpretation of interdependencies is slightly different from Levitt's, but the conceptual similarity is easily recognizable.

Schwingenschloegl affirms that reciprocal interdependencies require a high degree of organizational integration for tasks to be accomplished effectively. Further, he suggests that the effective coordination of the supply chain will involve the transformation of sequential tasks into reciprocal tasks. Though not explicitly stated by

Schwingenschloegl, it can be asserted that reciprocal interdependencies management approaches are applicable to facilitate supply chain management.

It is not surprising the reciprocal interdependencies are being discussed in the context of supply chain management, given that the trends of the past 20 years have been toward developing “core competencies” and doing less work “in-house.” Managing the reciprocal interdependencies in the context of in-house processes is far less complex than those that are not in-house. Product development decision making in the context of the increased complexity of supply chains adds more opportunities for error.

Verganti (1998, chapter 11) asserts that reciprocal interdependencies are the knowledge links between activities or entities. They represent the information exchange that takes place between activities/entities in order to solve a problem (or, address a question) during the product development lifecycle. Though not specifically stated by Verganti, it can be postulated that reciprocal interdependencies occur when the accomplishment of ongoing tasks requires a mutual exchange of continuously updated/revised information between activities/entities.

Reciprocal interdependencies can exist between various types of entities, activities, or teams. Verganti’s examples of reciprocal interdependencies interactions that take place during the lifecycle of a product are illustrated below:

Customer expectations ↔ Enterprise manufacturability (internal – external)

Existing product design ↔ Next-generation product design (common-new; across time; sequence or order)

Design concepts ↔ Product/process technologies (technically specific)

Product lifecycle stage ↔ Subsequent/prior product lifecycle stage (large groups of resources; across time; sequence or order)

Figure 1.3 Types of Product Lifecycle Reciprocal Interdependencies

Verganti goes a step further and affirms that in order to manage reciprocal interdependencies, the anticipated requirements of one activity must be systematically balanced (traded) against the known (or forecasted) constraints and opportunities of another activity. Though not specifically stated, it can be reasoned that when the anticipated requirements are in the same format as the forecasted opportunities, then knowledge flow between the activities can be automated and improved.

Verganti's definition of reciprocal interdependencies is broad in context, and it is geared toward the exchange of knowledge and information. It is slightly different from other discussions of reciprocal interdependences, but that does not detract from its usefulness. Even though the typical organizational structures and processes used do not always effectively manage the reciprocal interdependencies that exist – they should. Further, there is a need for strategies and approaches to manage reciprocal interdependencies that exist, and Verganti goes to the next level offering approaches for accomplishing this end within the context of teaming/IPTs and concurrent engineering.

1.3.2 Reciprocal Interdependencies Management

In the sections that follow, the key concepts related to Verganti's approaches in the context of reciprocal interdependencies management (RIM) are discussed. First, feedforward planning (as opposed to feedback planning) is defined. Next, the concepts of selective anticipation and commonality are presented.

1.3.2.1 Feedback Planning versus Feedforward Planning

The source material for this section is primarily due to the work of Verganti. (1998, chapter 11.) The information that follows contains material that has been paraphrased based on this reference unless otherwise noted.

Feedback planning is a reactive, after-the-fact, approach to managing RIs. The future constraints and opportunities are assumed to be at such a high-level of uncertainty in the early stages of product development that attempting to account for them is not worthwhile. An example of feedback planning from Figure 1.3 involves designing a product and then considering process technologies after the design is manufactured. The general consensus is that the range of possibilities for manufacturing a particular design configuration is just too large. When the number of design unknowns substantially decreases and design rigidity increases, then the engineering design will react to feedback generated. This can be an effective approach as long as engineering changes do not significantly impact performance.

Feedforward planning is a proactive approach to managing reciprocal interdependencies. The future constraints and opportunities that exist, such as in-house and supplier process capability, are anticipated and accounted for as early as possible at the level of detail required for effective decision making. Hence, if a new product should require something "totally new," this situation quickly comes to the forefront of the development process. The assumption is that the time spent on accounting for future constraints and opportunities are a worthwhile expenditure, and that it will more than cover the cost of engineering changes. In addition, improvements in cycle time and quality are expected additional benefits.

While feedback planning may be advantageous in some situations, the documentation of such situations is not readily available in the literature. Conversely, the negative impacts of engineering changes, which include rework, scrap, and increased total product costs, are well documented. (Fujimoto, 1997; Hayes et al., 1988; Meredith and Mantel, 1989; Trygg, 1991.) The majority of research and opinion indicate that feedforward planning is likely the best approach to managing reciprocal interdependencies. However, the implementation of feedforward planning is a very complicated undertaking because of the knowledge management complexities and issues its implementation involves. In the next two sections, the key components of Verganti's feedforward planning strategy are discussed, i.e., selective anticipation and commonality. A discussion of knowledge management complexities related to feedforward planning is presented following the section dealing with factors affecting successful RIM.

1.3.2.2 Selective Anticipation

Selective anticipation is an approach that Verganti discusses in the context of product development, RIM, and feedfoward planning. In order to manage reciprocal interdependencies, the anticipated requirements of one activity must be *systematically* *balanced* (traded) against the known (or forecasted) constraints and opportunities of another activity. In Verganti's writings, this systematic balancing is referred to as "selective anticipation."

> *"Selective anticipation consists of anticipating only a limited amount of information that allows one to verify the coherence between the product concept and the future constraints. Dedicating the most attention on a few critical areas."*

Verganti offers an example of selective anticipation dealing with helicopter design and weight, within the context of the product development process. Weight targets are normally identified early in the design process, are a critical element of the design, and play a greater role in early decision making strategies than design information that is not going to be known or identifiable until later. *(Similarly, systems and analytical approaches that are not sensitive to weight will not be as useful during conceptual design. Likewise, approaches that are used later could be made useful earlier if they were restructured in such a way as to be sensitive to weight.)*

Within the context of conceptual design decision making, selective anticipation involves recognition of:

- Types of design information
- Patterns of design information
- Timing of design information
- The need for future constraints and opportunities to be sensitive to information identified via selective anticipation.

Selective anticipation is one of the most difficult aspects of RIM and feedforward planning to apply because it requires proactive thinking on many levels of project planning and management, technical processes and tools, and design characteristics.

1.3.2.3 Commonality

Another concept that Verganti discusses in the context of RIM and feedfoward planning is systemic learning. Verganti's approach involves the recognition of the requirement for systemic learning. Systemic learning is defined as *"the capability of a company to learn from past projects and to incorporate experience."*

A minor extension of Verganti's definition of systemic learning is the application of what is referred to in industry as "commonality," i.e., the shared features and/or attributes from past endeavors. Commonality is the mechanism this research uses to accomplish certain aspects of systemic learning.

In general terms, if a system of people, facilities, and equipment is to be reused on a new project, more than likely, there is a tremendous amount of "known" information that can be reused. The faster the enterprise understands and can anticipate what will occur based on past experiences and available information, then new designs that are truly "new" will more quickly get the emphasis and planning needed. Figure 1.4 illustrates the concept.

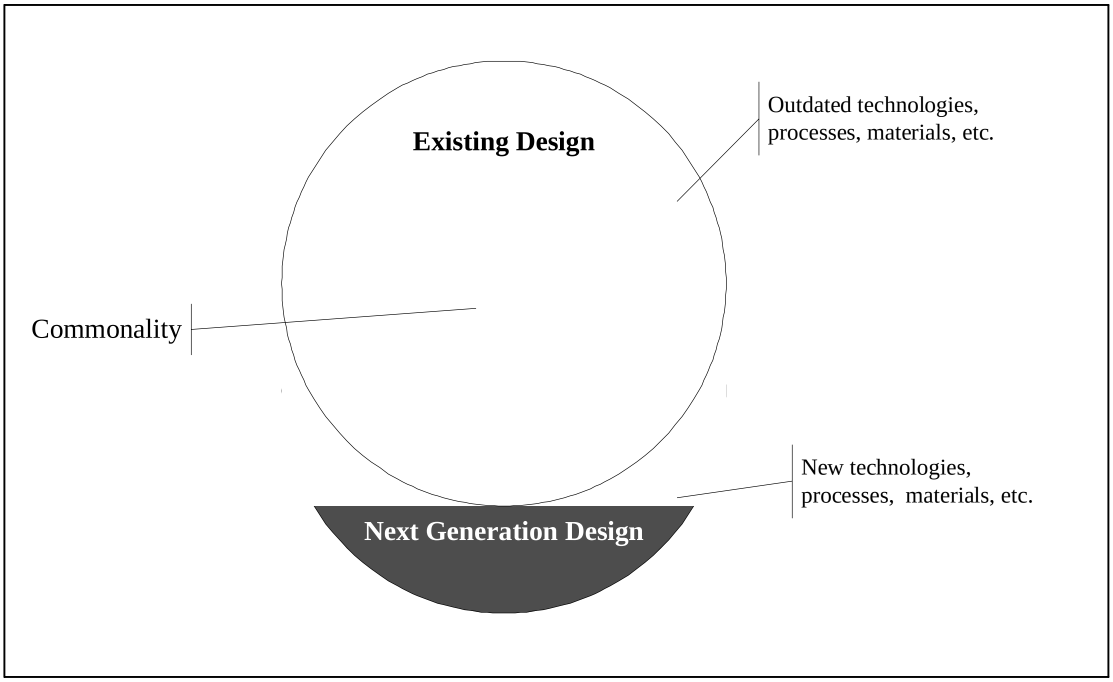


Figure 1.4 Commonality: The Potential for Knowledge Reuse and Systemic Learning

The application of commonality provides a large list of features, attributes, and processes that are potentially shared between past and future endeavors. However, the application of selective anticipation determines which of these elements will come to the forefront in the development of systems and methodologies to support product development decision making during the early stages of design. Though Verganti does not explicitly use the word "commonality," it is not a significant deviation from his discussion of systemic learning, and it is shown later in this research to be an important element of feedforward planning application. In the next section, the factors affecting/indicating successful RIM are discussed.

1.3.3 Factors Affecting/Indicating Successful RIM

Verganti's study revealed several factors that affect or indicate the successful implementation of RIM strategies. These factors are superficial anticipation, early process engineering, preplanning knowledge, and feedforward effectiveness. The basic definitions of these concepts are discussed in the paragraphs that follow. (These concepts will be discussed more in-depth later in Chapter 6.)

Superficial anticipation results in a baseline of assumptive information that has limited definition from which to make meaningful change or adjustment. Companies that are effective in reciprocal interdependencies management consider and manage important information earlier, and they create a baseline that is useful during multiple stages of product development. Companies that do not do well in RIM confuse selective anticipation with superficial anticipation.

Early process engineering entails collecting large amounts of relevant information prior to need and organizing the information in accordance to constraints and opportunities identified via selective anticipation. In particular, information related to specific technical tasks, such as manufacturing processes, would be considered early process engineering information. Companies that are not effective in RIM gather large amounts of data, but do not make it useful to teaming decisions.

Preplanning knowledge is the ability to identify the tasks to be accomplished and questions to be addressed in advance of the availability of specific task information. Preplanning knowledge includes items such as checklists, contingency plans, and procedures for handling "new" requirements. Preplanning knowledge also includes formal procedures and documents between activities. Companies that do better in preplanning knowledge do better in overall RIM and feedfoward planning.

Feedfoward planning effectiveness is the capability of a company to anticipate constraints and opportunities and avoid rework and other associated problems. Feedforward effectiveness is not directly measured by overall product development project performance as measured by sales and product functionality. Just because a product sells and functions properly does not mean that the product development process utilized was an efficient one. Verganti uses a fuzzy function to measure feedforward planning effectiveness that is sensitive to the occurrences of: 1) rework, 2) engineering changes, 3) unanticipated product cost increases, and 4) missed time to market estimates.

In Verganti's study, there were companies that believed they were utilizing concurrent engineering in their teaming efforts, yet they had poor results because they were not managing reciprocal interdependencies. Companies with better results with regard to feedforward planning effectiveness were also doing better in their utilization of selective anticipation and commonality to anticipate constraints and opportunities.

1.4 Feedforward Planning Knowledge Management Issues

Knowledge management is defined as:

> "*A range of practices and techniques used by organizations to identify, represent and distribute knowledge, know-how, expertise, and intellectual capital and other forms of knowledge for leverage, reuse, and transfer of knowledge and learning across the organization.*"
> (Nuschke and Jiang, 2007).

Further, there are two basic types of knowledge management: personalization and codification. Personalization is less dependent on systems and more interpersonal. Codification involves the systematic classification and storage of knowledge to address predefined questions and issues. (Alavi and Leidner, 2001.)

There are four knowledge management issues that currently inhibit the effective utilization of feedforward planning to manage reciprocal interdependencies. There is some overlap between feedforward planning knowledge management issues and the previously identified product development obstacles and concurrent engineering problems. However, this is not surprising given that multifaceted problems quite often trace back to the same, or very similar, root causes. Each of the feedforward planning knowledge management issues is discussed in the sections that follow.

1.4.1 Knowledge Management Strategy is Inhibited by Enterprise Culture

As discussed earlier, in many corporate cultures there is still a general reluctance among personnel to share knowledge, information, and expertise. All are often viewed as sources of individual or functional power. (Asideu and Gu, 1998; Austin et al., 2001; Pratt, 1984; Tolometti and Saunders, 1998; Vollerthun, 1998; Wierda, 1990). In order to effectively anticipate and account for future constraints and opportunities, the knowledge and learning of individuals and functions will ultimately have to take a backseat to the knowledge and learning needs of the enterprise.

1.4.2 IPT Knowledge Management Prior to Design Release is Dependent Upon Personalization

When the use of concurrent engineering and integrated product teams (IPTs) became popular in the early 1990s, many organizations responded by keeping the same functional personnel and systems, and merely collocated the respective individuals closer to engineering earlier in the design stage. The end result was a multifunctional team that relied heavily upon a personalization approach to knowledge management prior to design release. Then, after design release, the traditional functional systems behaved exactly as they had before.

One downside of heavy reliance on individuals to carry the knowledge and learning experience of the enterprise is that both become very subjective in nature as opposed to objective. Another negative is that if ten individuals in an organization have one level of expertise, and five have lesser experience, then the inexperience of the five can cause preventable errors to ripple throughout the entire process. Likewise, when an individual leaves the organization, then the knowledge and experience leaves as well, and a good method of training new replacements typically does not exist. (Haque, 2003; Valdez and Kleiner, 1996.)

In order to utilize feedforward planning to manage reciprocal interdependencies, the anticipation of constraints and future opportunities must become more standardized. This standardization will ensure that members of the IPT have the best available information, and that the variability in approach is reduced.

1.4.3 Functional Knowledge Management After Design Release is Not Codified for Reuse

Each of the activities in the generic product development process presented in Chapter 2 has one or more systems that support its efforts. However, the knowledge required to utilize these systems is not codified for reuse beyond the task at hand. (Andersson et al., 1995; Austin et al., 2001; Ou-Yang and Lin, 1997; Park et al., 2002; Xiong, 2003).

For example, after a design is actually released, a planning expert creates routings and work instructions; but the reasoning behind why one process was selected over another is not recorded. Similarly, manufacturing engineering studies are used to select processes and set up fabrication areas, but the knowledge within these studies is not codified for reuse in future decision making. Increased codification and reuse are essential for efficient application of feedforward planning strategies.

1.4.4 The Knowledge Management Strategy Does Not Fully Utilize Selective Anticipation and Commonality Opportunities

As defined by Verganti, *selective anticipation* is a narrowing process an enterprise uses to identify the minimum amount of information that will be required to make a future decision. *Commonality* is the shared features/attributes from past endeavors. In order to use feedforward planning to manage reciprocal interdependencies during the early stages of product development, the enterprise knowledge management system must become efficient in the utilization of selective anticipation and commonality.

Due to the advances in computer technology, most enterprises have a tremendous capability to generate and store data. However, quite often the data from past endeavors are not organized (or codified) in a manner that makes it meaningful to future conceptual design decision making with incomplete (sketchy) information.

In addition, the overabundance of data can actually lead to enterprise inefficiencies. Analysts supporting product development activities spend large amounts of time trying to take data collected for one purpose and reformat it in order to make inferences to product development decision making. This reformatting procedure is referred to as being an ad hoc (for this purpose) approach.

The reformatting of data is not within itself a bad thing. In fact, in order to utilize information from the systems of various functional organizations during the early stages of design, considerable reformatting and/or data grouping strategies are required. The significant difference is that approaches need to be standardized, computerized, and become a part of the collective knowledge of the enterprise. Having different, segmented approaches that are left to the devices of individuals is not the preferred approach.

In order to use feedforward planning to manage reciprocal interdependencies during the early stages of product development, the enterprise knowledge management strategy must use selective anticipation to identify information availability and corresponding systems sensitivity requirements. In addition, commonality strategies must be a part of enterprise systems design in order to facilitate the codification of knowledge.

When the four primary feedforward planning knowledge management issues are combined with prior issues related to product development obstacles and concurrent engineering problems, the need for fully integrated RIM-based decision support systems is overwhelmingly supported. Hence, the incorporation of a conceptual framework for a RIM-based decision support system is incorporated into this research.

1.5 Research Objectives

The objectives of this research are to:

1) Systematically apply Verganti's findings and concepts (i.e., reciprocal interdependencies, feedforward planning, selective anticipation, etc.) to demonstrate how they can be used to improve IPT decision making during the early stages of product design.
2) Address the information needs/issues associated with product development process obstacles, concurrent engineering problems, and feedforward planning knowledge management issues by developing the following:
    a. Generic product development process diagrams
    b. Definition of integrated product team members and decisions
    c. Conceptual framework for a RIM-based DSS for use during conceptual design of an aircraft NC machined bulkhead
3) Examine the potential usefulness of using RIM concepts in the construction of enterprise systems by comparing the defined RIM-based DSS to other approaches found in the literature.

1.6 Scope of the Research

Verganti's research and the associated findings are based on 12 case studies of Italian and Swedish companies, and for the sake of confidentiality, none of the companies are specifically identified. In order to make Verganti's findings relevant to companies in the U.S. and this author's work experience, some extrapolation is necessary.

As a part of this research, an investigation is undertaken to determine how well U.S. companies have embraced concurrent engineering and whether the claimed benefits have been realized. The results of this investigation are presented in Appendix A and some results have been presented in Section 1.1.2. The results are similar to Verganti's in that they are mixed, i.e., success is not widespread and commonplace. In addition, many of the same factors that stood in the way of successful results identified in the investigation were similar to those identified in Verganti's research.

In order to demonstrate the application of RIM-based strategies in the context of a conceptual decision support system, it is necessary to extrapolate further to a specific case/industry. For this research, the specific case of aircraft manufacturing in the defense industry is used. This industry is chosen for two reasons: 1) the need for improved feedforward effectiveness in the defense industry and 2) this author's work experience.

Verganti's study reveals that feedfoward planning effectiveness is measurable using criteria such as the amount of rework, engineering changes, unanticipated product costs, and missed time-to-market estimates. In other words, if an enterprise is not doing well in these areas, then their feedforward planning effectiveness is likely less than desirable. No matter what the enterprise may believe it is accomplishing with regard to teaming, concurrent engineering, and the anticipation of constraints and opportunities (feedforward planning), it is ineffective if these factors (e. g., rework, engineering changes, cost and schedule growth, etc.) are not improving.

A specific study geared toward aircraft manufacturing could not be located. However, several studies are available that deal with military contracting and defense acquisition at large. Swank et al. (2000) report that the Office of the Secretary of Defense (OSD) funded a five-year study on acquisition performance trends. The study covers a 16-year period in which no program metrics show improvement in cost or schedule overruns. The overruns in cost and schedule performance were 40% and 60%, respectively, and the study concludes: “there is a lack of trend data to determine if DOD acquisition management is improving.”

In addition, there are specific aircraft examples that indicate poor feedforward planning effectiveness. In the 1990s, the F-22 Raptor program was one of the first to use concurrent engineering, and the project experienced some of the worst performance measures in history. The United States Government Accountability Office (GAO) determined that the predominant cost and schedule growth driver was traceable to management of data that should have occurred prior to manufacturing start. (GAO, 2002.) In 2005, the F-35 Joint Strike Fighter was labeled as the most expensive fighter in history, and cost overruns were causing international partners to cut planned purchases, which will ultimately drive up the cost per unit. Some fear that the F-35 is in a cost-induced “death spiral.” (Aero-News, 2005.) If aircraft manufacturing enterprises were doing well in the areas of feedforward planning effectiveness, then one would suspect that their performance metrics would be better and that the metrics would be improving. However, in general, this does not appear to be the case, so it is reasonable to assume that there is great deal of room for improvement.

Lastly, in order to demonstrate Verganti's concepts within the context of a RIM-based decision support system (DSS), the scope of the specific tasks has to be limited. In this research, an operational DSS is not developed. Instead, a conceptual framework for a RIM-based DSS is presented using the specific case of an aircraft NC machined bulkhead.

1.7 Research Limitations

It is beyond the scope of this research to develop the ultimate generic product development process or decision support system conceptual framework for an aircraft manufacturing enterprise. Further, Verganti's concepts are not to be misconstrued as the "end all" when it comes to anticipating manufacturing constraints and opportunities in the concept generation phase and improving teaming. Likewise, the work experiences of this author are not representative of all possible experiences. Therefore, the deliverables of this research should not be confused with an actual improvement within a specific enterprise, but instead provide insights into the complexities involved in the difficult work of design and implementation of sophisticated systems to address labyrinthine decisions.

Another limitation of this research is the lack of published works related to actual industrial endeavors. As noted by Shumaker and Thomas (1998) in Chapter 10, "Integrated Processes in Defense Manufacturing," of the book Integrated Product and Process Development: Methods, Tools, and Technologies - the approaches, models, successes, and failures of most companies are held within their proprietary annals. Verganti also noted that while many tools and approaches are proposed in the literature, there is a lack of empirical validation.

In Chapter 8 of this dissertation, comparisons are made between the conceptual framework presented in this research and other approaches in the literature using a qualitative assessment tool. It is understood that a quantitative assessment tool is preferred, but is not possible due to a lack of detail in published works as well as the complexities of data translation to make sure comparisons.

Finally, the work accomplished in this research does not address quantitative uncertainty or risk, and the feedforward planning model presented generates only traditional point estimates. The consideration of uncertainty would significantly increase complexity and is beyond the scope of this research. The author believes uncertainty can more effectively be added once a solid baseline is established. Therefore, the consideration of uncertainty is believed to be an extension beyond this research.

However, if uncertainty modeling and management were explicitly considered, then the following list provides a starting point for the general tasks that would need to be accomplished:

1) Define the key input parameters that affect the value to be estimated, and develop a deterministic model.
2) Estimate the uncertainty in each process cost estimating relationship (CER).
3) Estimate the probability of process occurrence.
4) Estimate the risk in each input parameter.
5) Analyze the estimate using Monte Carlo simulation.
6) Based on the results of the Monte Carlo simulation, make user appropriate decisions.

If additional analysis using multiple models simultaneously was found to be appropriate, then some type of response surface methodology (RSM) could be applied that includes risk and uncertainty. RSM enables the decision-maker to change the initial input parameters to detect the effects of the responses in a time-efficient manner.

1.8 Dissertation Outline

The remainder of this dissertation is organized as follows.

Chapter 2 discusses a generic product development process and associated IDEF0 diagrams created as a part of this research and correlates RIM approaches to the activities in the generic product development process. The development of the generic product development process addresses specific information needs identified in Chapter 1 that are not currently provided in the literature. Chapter 2 is presented before the literature review because the activities on the generic product development process diagrams are used to organize the literature review.

Chapter 3 presents the literature review of relevant research organized using the activities of the generic product development process presented in Chapter 2. Organizing the research based on the product development process supports Verganti's assertion that many tools in the literature lack insight into the complex mutual interactions that take place during conceptual design decision making.

In Chapter 4, some of the commonly held views of the product development life cycle are discussed in the context of RIM. When appropriate, relevant assertions are offered in the context of aircraft manufacturing in the defense industry.

In Chapter 5, the integrated product team is defined for this research. As identified earlier in this chapter, there is a need to better define the members, roles, and responsibilities of an IPT before attempting to develop systems to assist them in decision making. As asserted by Verganti and supported by the literature review, too often the important step of placing the system in the appropriate empirical context is overlooked by those espousing to develop new systems and approaches for improving conceptual design decision making.

Chapter 6 presents the conceptual architecture of the RIM-based DSS developed in Chapter 7, as well as a process flow to illustrate a decision making instance. Chapter 6 is offered as an executive summary of information to be presented in Chapter 7 to better orient the reader.

In Chapter 7, the conceptual framework of a RIM-based decision support system (DSS) is systematically developed. If the reader is not familiar with common aircraft terminologies and concepts, then Appendix B should be read before Chapter 7. Appendix B provides a sampling of information related to aircraft manufacturing. The appendix is provided in order to shorten Chapter 7. There are many topics covered in Chapter 7 that are commonly used in aircraft manufacturing and do not warrant a great deal of explanation within the body of the dissertation.

Chapter 8 compares the defined RIM-based DSS to other approaches in the literature using a qualitative assessment tool. Ten other approaches are qualitatively compared.

Chapter 9 discusses conclusions and future work.

Appendix A contains the concurrent engineering investigation referenced in Chapter 1.

Appendix B contains technical information referenced in Chapter 7.

CHAPTER II

REFINING THE GENERIC PRODUCT DEVELOPMENT PROCESS

In Chapter 1, the obstacles and problems related to product development improvement and concurrent engineering are discussed. One of the identified needs is a generic product development process. This need correlates with Verganti's concepts related to reciprocal interdependencies (RIs) and supports his approach. Verganti asserts that RIs are the knowledge links between activities or entities, and they represent the information exchange that takes place between activities/entities in order to solve a problem (or address a question) during the product development lifecycle.

Further, Verganti reports that even though many tools had been proposed in the literature, they lack insight into the complex mutual interactions taking place in conceptual design decision making. The generic product development process diagrams illustrate the complex interactions and when the literature is organized using the generic product development process diagram, Verganti's conclusion is supported because the majority of the published works do not consider multiple activities simultaneously. (1998, chapter 11.)

The generic product development process diagrams and associated activities serve as a high-level frame of reference for the remainder of the information presented in this research. Further justification of the need for these diagrams and the diagrams themselves are presented in the next section.

2.1 Generic Product Development Process (GPDP) for a Manufacturing Enterprise

As discussed in Chapter 1, one of the first steps toward improving the product development process and the associated conceptual design decision making for a manufacturing enterprise is to define the product development process. Ulrich and Eppinger (2000) define the product development process as follows: “The sequence of steps or activities which an enterprise employs to conceive, design, and commercialize a product.”

Further, Ulrich and Eppinger define the product development process as a series of six phases:

0. Planning (numbering starts at zero because it precedes product launch or approval)
1. Concept development
2. System-level design
3. Detail design
4. Testing and refinement
5. Production ramp-up

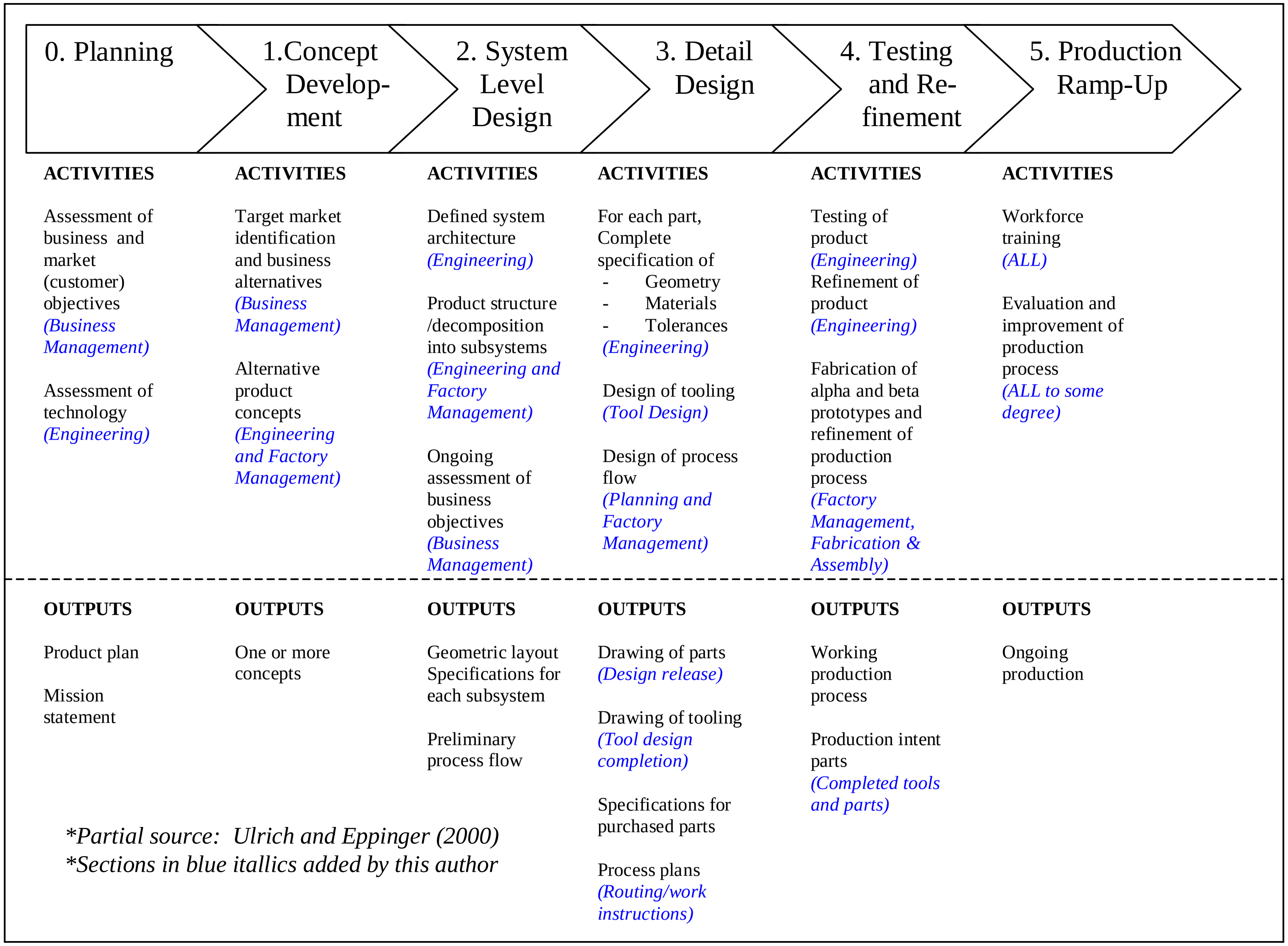
While Ulrich and Eppinger (2000) focus on six generic phases and the basic activities to be accomplished in each phase (See Figure 2.1) much of the literature related to product development process improvement is organized differently. The available literature related to product development process improvement normally groups the activities listed in the six phases by the various organizations that accomplish them, the enterprise systems they use to accomplish a task, or some combination thereof. Examples of common "task groups" within a manufacturing enterprise discussed in the literature include engineering design, cost estimating, process planning, detail part fabrication, and assembly. Examples of common enterprise systems discussed in the literature support engineering, manufacturing, and business management (business management being something other than engineering or manufacturing.)

This does not imply that activities such as marketing (i.e., the identification of customer requirements, advertising, distribution, selling, public relations, market research), logistics, human resource management, and procurement are not important to the product development process. They are undeniably part of the value chain of any organization. However, these activities are often not the specific focus of the literature related to improving product development decision making during the early stages of design. While these tasks are a part of the generic product development process to be presented later, their contributions are treated as mechanisms/resources or controls that support a larger activity group - with the exception of the identification of customer requirements, which is treated as a primary input.

It should be noted in a functionally oriented enterprise, the organization's name nearly becomes synonymous with the activities that the organization performs. For example, "business management" develops the tools for managing business, such as schedules, budgets, and financial controls, "engineering" creates designs and performs tasks associated with the test and validation of those designs, "planning" generates work instructions, “fabrication” manufactures parts and tools, and so on. In the literature, as in the workplace, the functional name of the organization quite often becomes “one in the same” with the activities it performs.

Therefore, for the purposes of this research, it is necessary to develop a generic product development process (GPDP) for a manufacturing enterprise that is function/activity oriented as opposed to Urlich and Eppinger’s six-phase approach. The GPDP emphasizes the activities and their associated deliverables, which are most commonly the subject of published research. Currently, a GPDP approach of this type is not documented in the literature, and hence, is considered a contribution of this research effort.

In Figure 2.1, the product development process of Ulrich and Eppinger (2000) has been edited to include the naming of the activities utilized in the IDEF0 diagrams presented in Section 2.2. The items in blue itallics are additions to the original six-phase approach. Please note that the use of IDEF0 diagrams is not directly correlated to the number zero in Ulrich and Eppinger (2000) the six-phased approach.



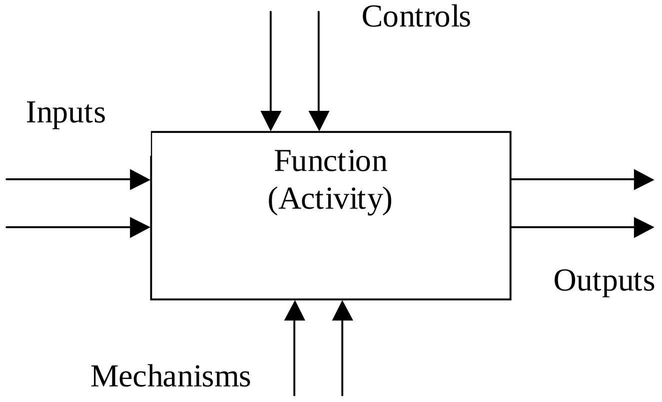
0. Planning	1.Concept Develop-ment	2. System Level Design	3. Detail Design	4. Testing and Re-finement	5. Production Ramp-Up
ACTIVITIES	**ACTIVITIES**	**ACTIVITIES**	**ACTIVITIES**	**ACTIVITIES**	**ACTIVITIES**
Assessment of business and market (customer) objectives *(Business Management)* Assessment of technology *(Engineering)*	Target market identification and business alternatives *(Business Management)* Alternative product concepts *(Engineering and Factory Management)*	Defined system architecture *(Engineering)* Product structure /decomposition into subsystems *(Engineering and Factory Management)* Ongoing assessment of business objectives *(Business Management)*	For each part, Complete specification of - Geometry - Materials - Tolerances *(Engineering)* Design of tooling *(Tool Design)* Design of process flow *(Planning and Factory Management)*	Testing of product *(Engineering)* Refinement of product *(Engineering)* Fabrication of alpha and beta prototypes and refinement of production process *(Factory Management, Fabrication & Assembly)*	Workforce training *(ALL)* Evaluation and improvement of production process *(ALL to some degree)*
OUTPUTS	**OUTPUTS**	**OUTPUTS**	**OUTPUTS**	**OUTPUTS**	**OUTPUTS**
Product plan Mission statement	One or more concepts	Geometric layout Specifications for each subsystem Preliminary process flow	Drawing of parts *(Design release)* Drawing of tooling *(Tool design completion)* Specifications for purchased parts Process plans *(Routing/work instructions)*	Working production process Production intent parts *(Completed tools and parts)*	Ongoing production

**Partial source: Ulrich and Eppinger (2000)*
**Sections in blue itallics added by this author*

Figure 2.1 Product Development Process Six-Phase Approach With Activity-Level Modifications

2.2 IDEFO Diagrams of the GPDP

Integration Definition for Function Modeling, IDEF, is a set of definition languages that have become standardized modeling techniques. IDEF0 is a method used to model the decisions, actions, and activities of an organization or system. The National Institute of Standards and Technology, NIST, released IDEF0 as the standard for function modeling in 1993. (NIST, 2002.) The basic layout and definitions related to an IDEF0 diagram is presented in Figure 2.2.



Function – an activity, action, process, or operation; typically begins with a verb (but not required), i.e., "fabricate part" can be viewed as synonymous with "fabrication"

Inputs – things "consumed" (e.g., data) or transformed

Outputs – things that are produced (e.g. reports, deliverables)

Mechanisms – things or resources used, but not consumed

Controls – things that ensure proper completion

Figure 2.2 IDEF0 Diagram Layout and Definitions

Figure 2.3 provides an overview of the generic product development process for a manufacturing enterprise. Figure 2.3 is intended to provide the reader with a single-page, executive summary of the generic product development process used in this research.

The red arrows in Figure 2.3 indicate Business Management controls that are developed by the Business Management activity and used by other activities. The blue arrows indicate the Factory Management controls developed by the Factory Management activity and used by other activities. The green arrows indicate the Engineering controls developed by the Engineering activity and used by the other activities. The outputs that are color-coded are permanent controls, in that, once developed in their final form they require an extensive change procedure before they can be altered. The controls maintain the continuity of how information is shared/used by the activities.

The functions/activities denoted on the generic process diagrams do not include a verb. As explained earlier, the collective group of tasks involved with "developing, testing, controlling, managing of the design" is simply referred to as "Engineering," and so forth. The acronyms used in Figures 2.3 through 2.7 are:

- WBS – Work Breakdown Structure
- CWBS – Contract Work Breakdown Structure
- SOW – Statement of Work
- ROM – Rough Order Magnitude (Initial estimates of schedule and cost are "rough" and provide a starting point. An iterative process and information refinement leads to final estimates of cost and schedule.)
- M&P – Materials & Processes
- EBOM – Engineering Bill of Material
- MRP – Material Requirements Planning
- FMS – Factory Management System
- ME – Manufacturing Engineer
- IE – Industrial Engineer
- Mfg Rep – manufacturing representative
- QA Rep – quality assurance representative
- IPT – integrated product team

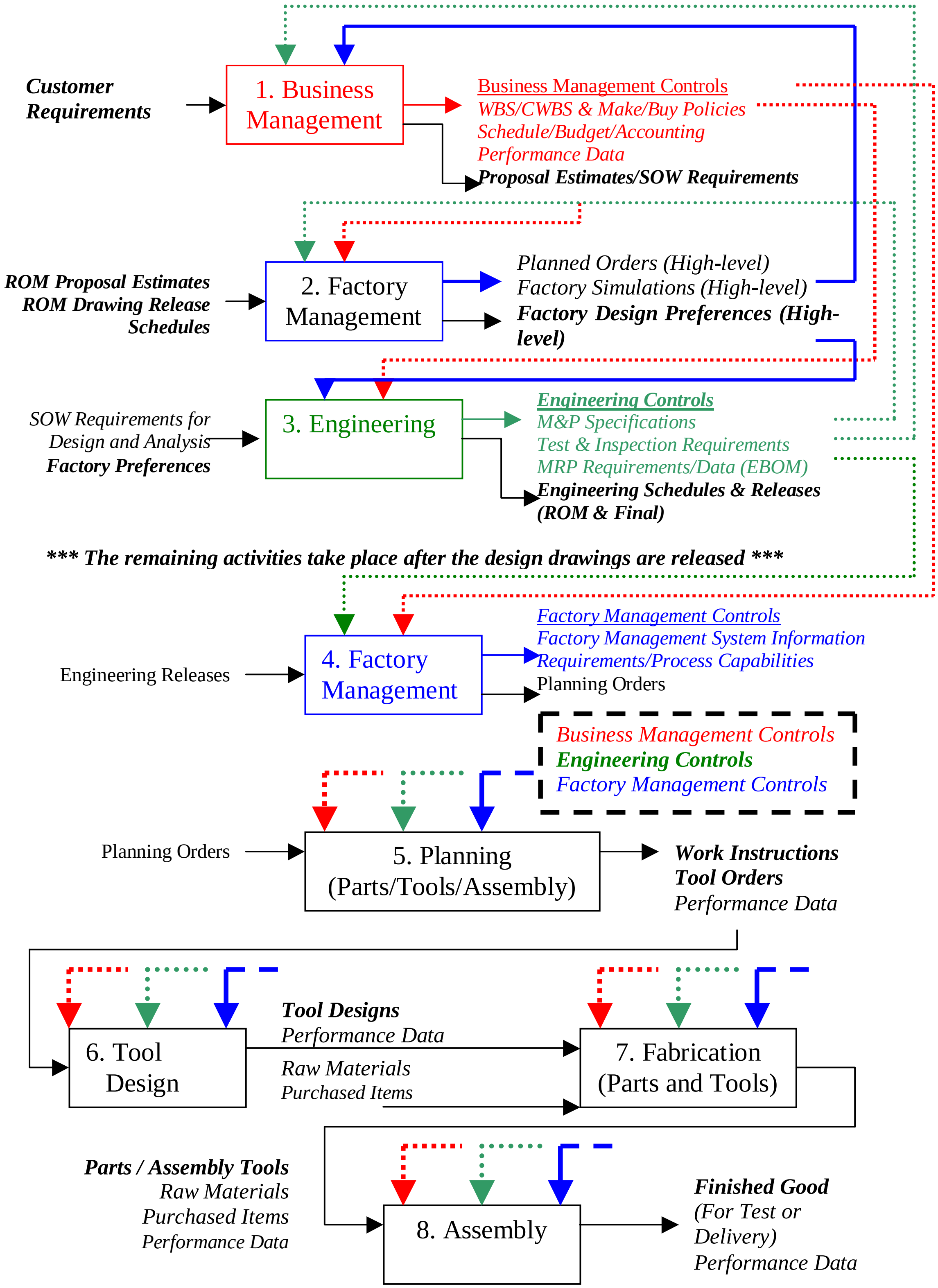


Figure 2.3 Abbreviated (High-Level) Generic Product Development Process Organized Using Eight Activities

Figures 2.4, 2.5, 2.6, and 2.7 provide IDEF0 representations of the activities involved in the generic product development process for a manufacturing enterprise. These diagrams provide details not included in Figure 2.3. The activities, inputs, mechanisms, controls, and outputs shown in these IDEF0 representations are used as a frame of reference throughout the remainder of this research.

The first three activities on the high-level IDEF0 representation, Business Management, Factory Management, and Engineering, take place before the release of the engineering drawings during the conceptual and preliminary design phases. "Business Management" is a collector activity for tasks that are not engineering or manufacturing.

The last five activities on the IDEF0 representation, Factory Management, Planning, Tool Design, Fabrication, and Assembly, take place after the release of engineering drawings during the detail design phase. The "Factory Management" activity is broken into two activities on the IDEF0 representation in order to more easily convey the tasks that occur *before* design release (Activity 2, Figure 2.4-bottom) and those that occur *after* design release (Activity 4, Figure 2.5-bottom).

The dashed line box containing the letters "IPT," indicate that the members of the IPT are part of these activities.

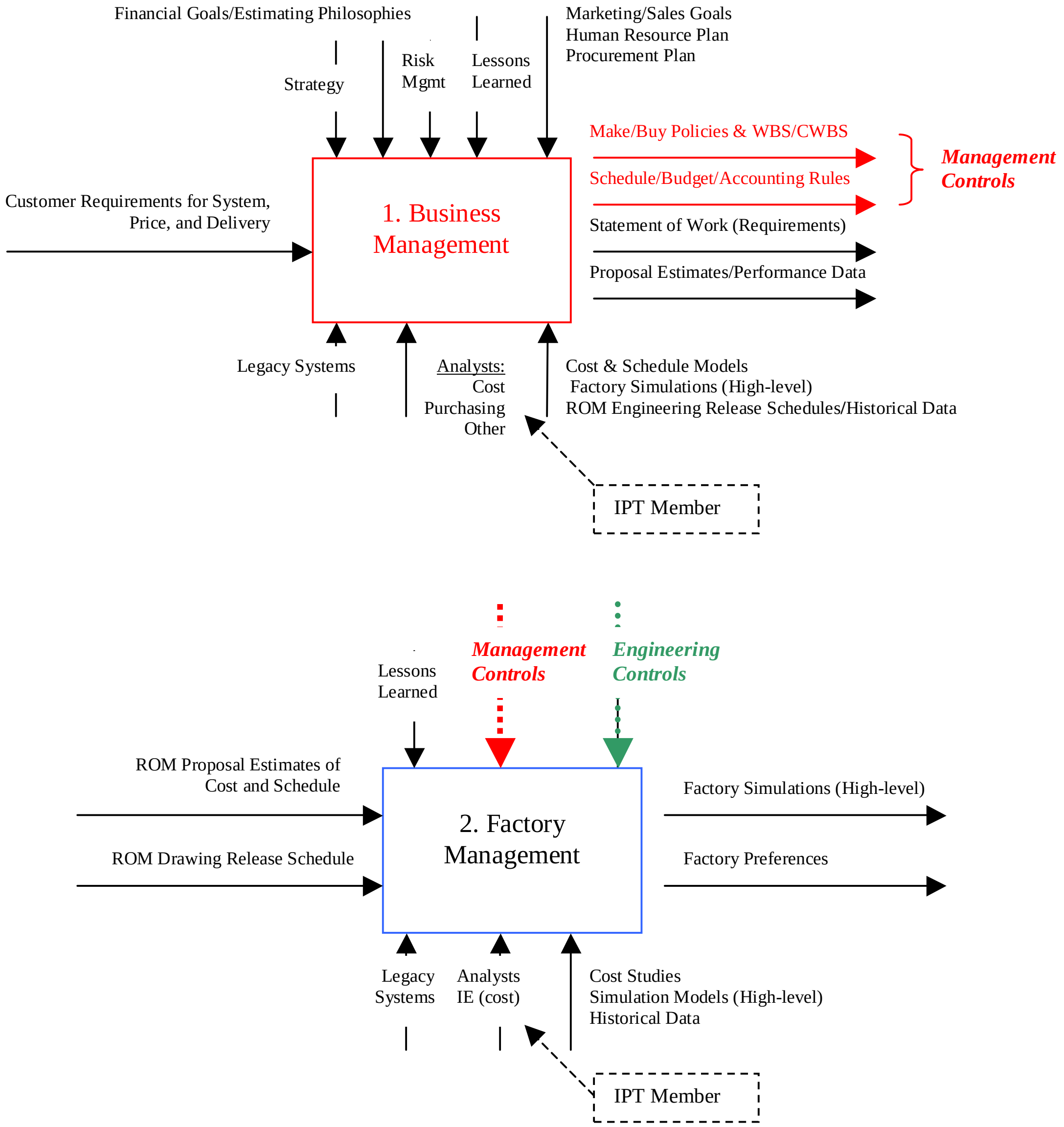
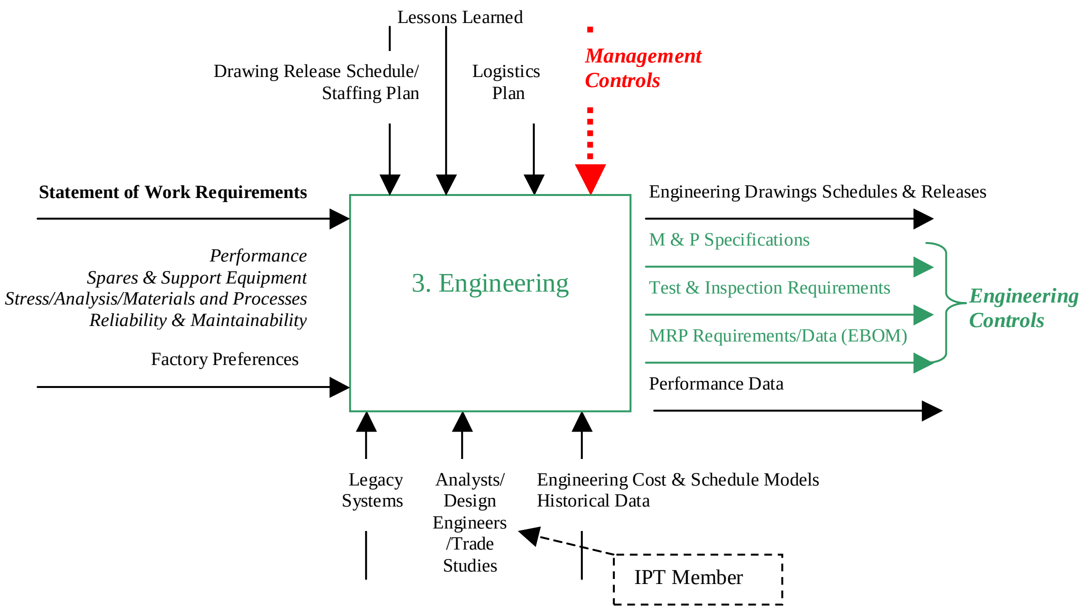


Figure 2.4 The Generic Product Development Process Activities Represented in IDEF0 Diagrams: Activities 1 and 2



**** The remaining activities take place after the design drawings are released *****

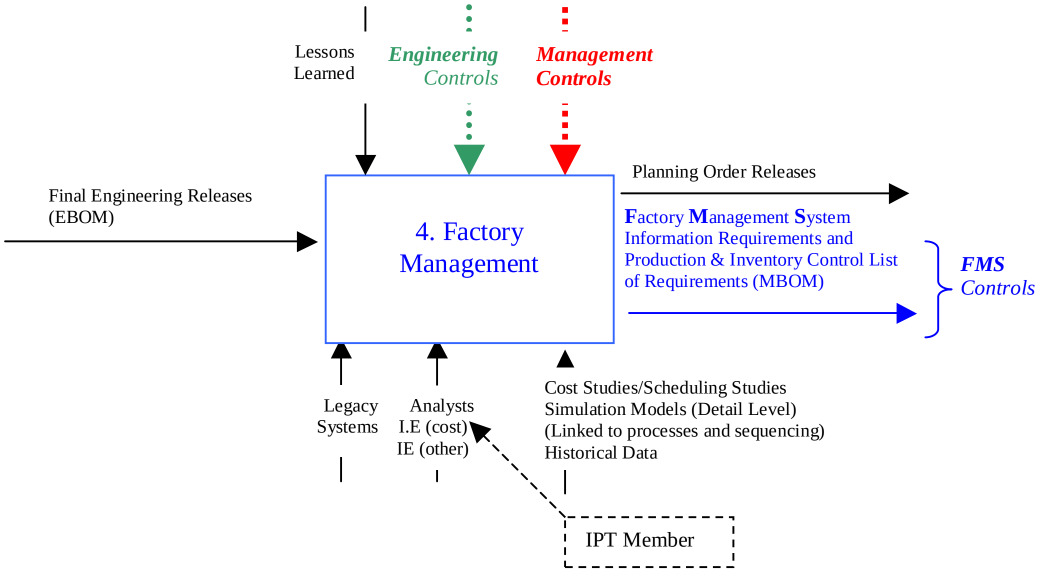


Figure 2.5 The Generic Product Development Process Activities
Represented in IDEF0 Diagrams: Activities 3 and 4

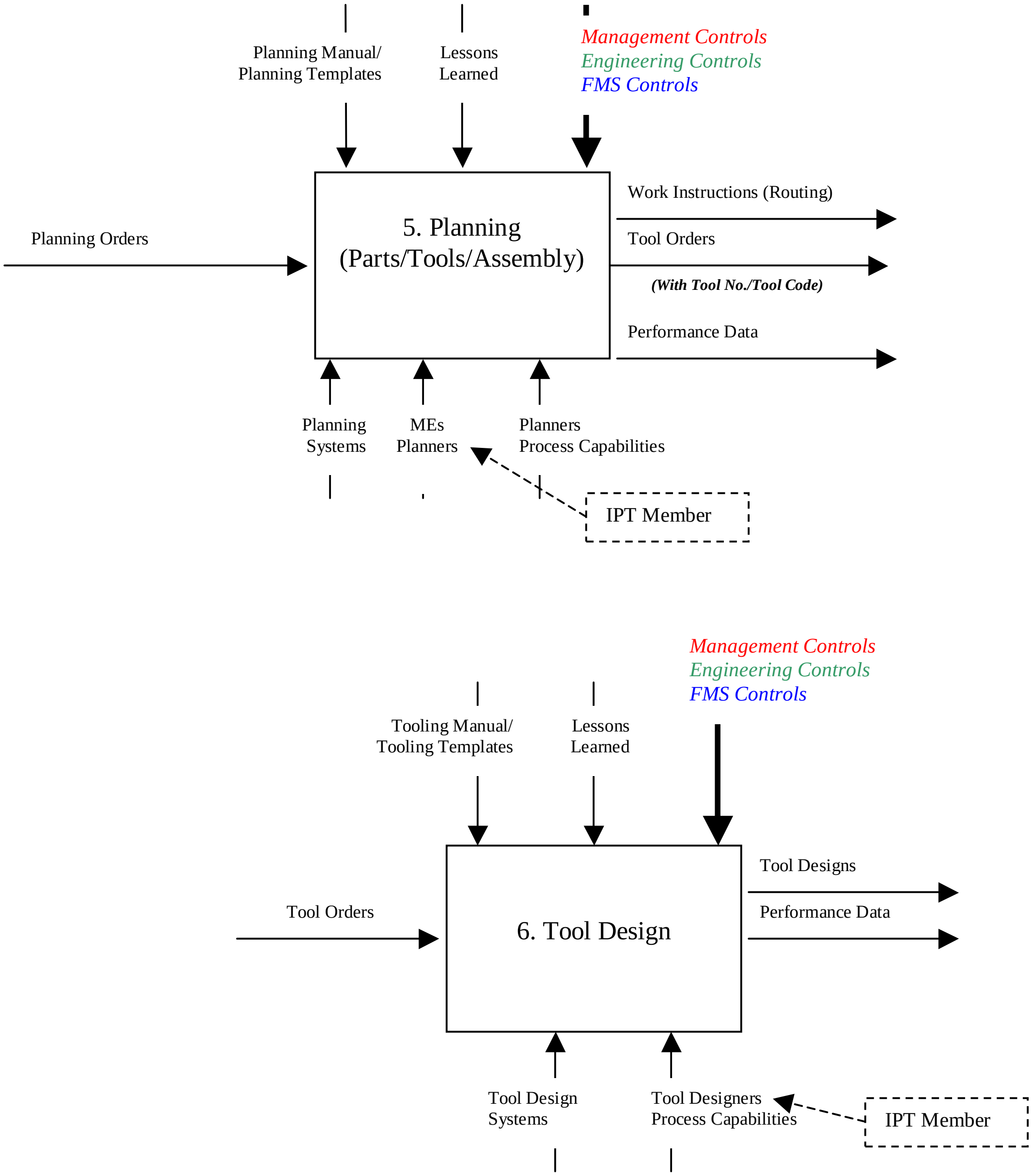


Figure 2.6 The Generic Product Development Process Activities
Represented in IDEF0 Diagrams: Activities 5 and 6

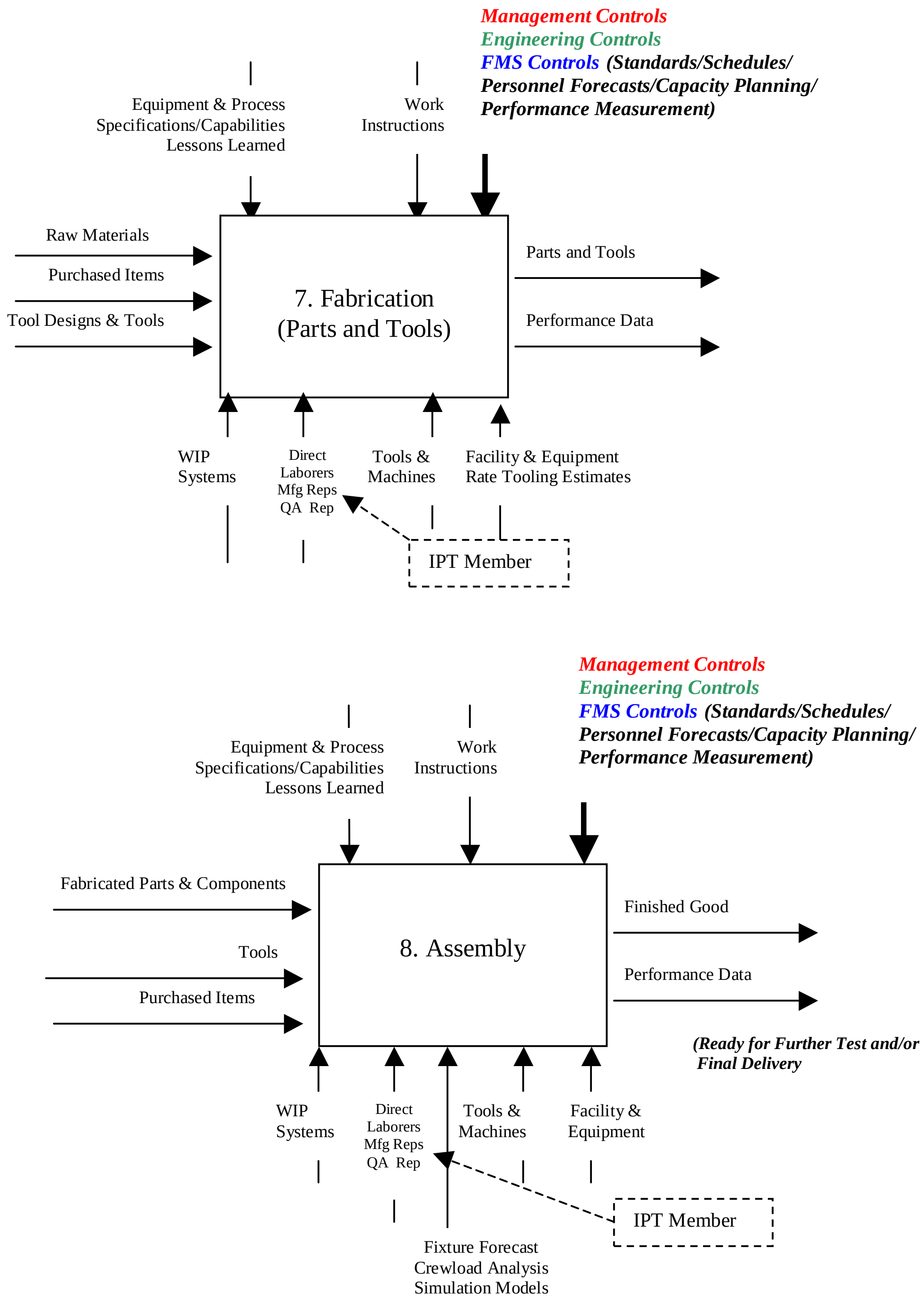


Figure 2.7 The Generic Product Development Process Activities Represented in IDEF0 Diagrams: Activities 7 and 8

2.3 Summary

In this chapter, the generic product development process (GPDP) IDEF0 diagrams are presented. The six-phased approach of Ulrich and Eppinger - planning, concept development, system-level design, detail design, testing and refinement, and production ramp-up – is reformatted using an IDEF0 approach. The IDEF0 approach utilizing functions/activities is more readily useful to correlate the literature review information and Verganti's concepts of reciprocal interdependencies, which utilize knowledge links between activities.

In the next chapter, the literature review is organized and discussed using the activities on the GPDP diagrams as the frame of reference. These activities are:

1. Business Management
2. Factory Management (before design release)
3. Engineering
4. Factory Management (after design release)
5. Planning
6. Tool design
7. Fabrication
8. Assembly

CHAPTER III

LITERATURE REVIEW

The competitiveness of an enterprise is greatly influenced by the cost, quality, and timeliness with which it brings new products into the marketplace. The majority of published works related to product development assert that 70-80% of the total cost of a product is committed during the early stages of product design. (Feng and Song, 2000; Lee and Kelce, 2003; Park et al., 2002; Shehab and Abdalla, 2001; Wang and Wang, 2002). Likewise, improvements to any stage of the product development process can be linked to corresponding enterprise improvements in time-to-market, quality, and global competitiveness. (Asiedu and Gu, 1998; Ferrelrinha et al., 1993; Hsu and Woon, 1998; Kroll, 1992; Rehmann and Guenov, 1998; Yang et al., 2003.)

Current literature contains many methodologies, frameworks, and systems that have the potential to improve product development process related decision making. This chapter reviews, organizes, and categorizes a significant sampling of literature using the generic product development process (GPDP) IDEF0 diagrams presented in Chapter 2 as a frame of reference. The effort results in the creation of a synergism of new product development knowledge, which is another contribution of this research.

Using the GPDP activities and associated deliverables identified in Figure 2.1, the literature is systematically grouped and discussed based on the activities addressed by the research methodologies. In addition, a high-level synopsis of the identified groups and findings are presented.

3.1 Categorization of Relevant Research

Over one hundred articles related to some aspect of product development process improvement and early design decision making were surveyed. The literature was then categorized using the generic process flow diagrams in Figure 2.3 through 2.7 as a frame of reference. The following nine groups resulted:

Group 1: Engineering Design Activity – Design Systems Emphasis

Group 2: Engineering Design Activity – Design Systems With Cost Emphasis

Group 3: Engineering Design Activity - Logistics Engineering Emphasis

Group 4: Engineering Design Activity – IPT Systems Emphasis

Group 5: Engineering and Planning Activities – Systems Integration Emphasis

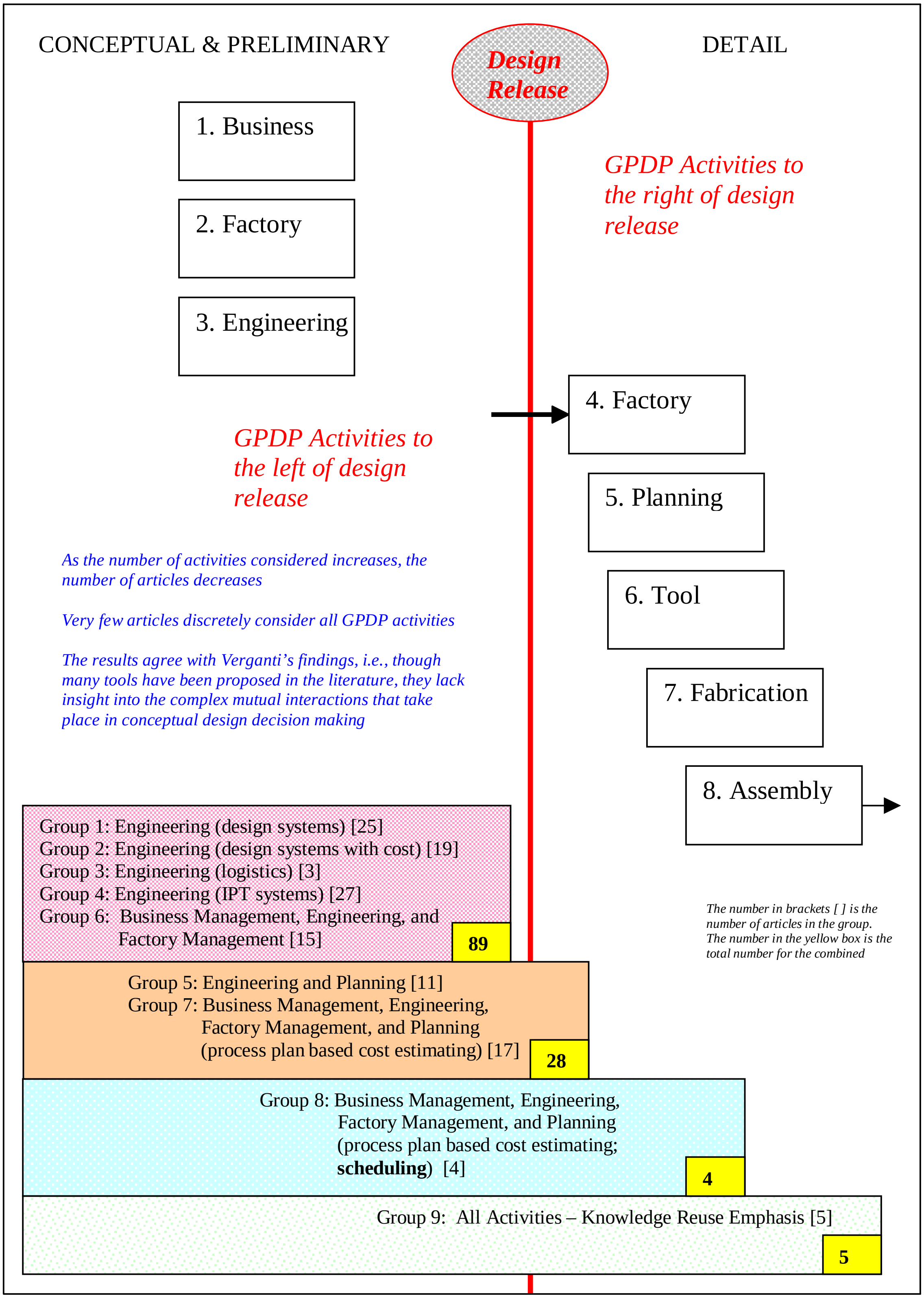
Group 6: Business Management, Engineering, and/or Factory Management Activities - High-Level Cost Estimation Tasks Without Process Plan Generation Emphasis

Group 7: Business Management, Engineering, Factory Management, and Planning Activities - Detail-Level Cost Estimation Tasks With Process Plan Generation Emphasis

Group 8: Business Management, Engineering, Factory Management, and Planning Activities - Detail-Level Cost Estimating and Scheduling Tasks Emphasis

Group 9: All Enterprise Activities – Knowledge Reuse Emphasis

The nine groups are further categorized in Figure 3.1 as follows:



As the number of activities considered increases, the number of articles decreases

Very few articles discretely consider all GPDP activities

The results agree with Verganti's findings, i.e., though many tools have been proposed in the literature, they lack insight into the complex mutual interactions that take place in conceptual design decision making

The number in brackets [ ] is the number of articles in the group. The number in the yellow box is the total number for the combined

Figure 3.1 Association of Literature Review Groups to GPDP IDEF0 Activities 1 Through 8

Figure 3.1 correlates the GDPD activities, the design release, the nine literature review groups, and the number of articles. The top portion of the figure contains the eight activities identified in the GPDP IDEF0 diagrams. Three activities that take place before design release and five that take place after design release.

The first block illustrates the literature in Groups 1, 2, 3, 4, and 6 are primarily dedicated to activities that take place prior to design release. The number of articles in each group is provided in brackets and the total number of articles is contained in the highlighted box.

The second block illustrates the literature in Groups 5 and 7 begin to include activities that take place after design release; primarily Planning and cost analyses. The number of articles in each group is provided in brackets and the total number of articles is contained in the highlighted box. The total number of articles in this block is three times smaller than the first block.

The remaining two blocks on the diagram are organized in a manner similar to the first two blocks. It is noteworthy that as the number of activities considered and complexity increases, the number of articles decreases.

3.2 Discussion of Categorized Relevant Research

In the sections that follow, each of the nine groups is discussed using the generic product development process IDEF0 diagrams from Chapter 1 as the frame of reference. In each group, an overview of methodologies and approaches is presented.

3.2.1 Group 1: Engineering Design Activity – Design Systems Emphasis

This group of research deals with the Engineering activity on the GPDP IDEF0 diagram and the design systems mechanism in Figure 2.5. The emphasis of the research is on improvements to engineering design systems used the early design stages of the product development process. The intended user is the design engineer, and the goal is to support better and faster design generation. Cost is not a direct consideration or demonstration in these approaches. In addition, while production rules are sometimes considered, there are no direct links to existing Factory Management Systems.

Blasi et al. (2000) suggest improvements in conceptual aircraft design using a multiconstraint genetic algorithm optimizer. A genetic optimizer is coupled with a sizing code to define preliminary aircraft configuration and sizing in the early stages of design.

Condoor and Weber (1999) present a model for conceptual design methodology that combines parameter analysis with robust design techniques. Two cases studies illustrate the application of qualitative design techniques prior to the development of concept details.

Fliedl (1999) applies natural language based requirements analysis to the design of information systems. Since system and information requirements are normally established via dialogues between potential users, it is postulated that by properly classifying texts that candidate lists of subjects, actions, and objects can be generated based on linguistic categories. This methodology has specific application to the development of engineering design systems or other types of information systems.

Grierson (1994) proposes the development of a computer-based capability for the application of evolutive-cognitive techniques during the early stages of design. The computational model is based on a neural network.

Irgens (1995) demonstrates how case-based reasoning could be used to provide design support during the early stages of product design. Information generated during the later stages of the product development life cycle would be stored in such a manner as to offer future advice. Cases are developed, and then stored in a historic advice for product prototyping (HAP) online system. Users input key criteria to search for past cases similar to present design problems.

Hira and Tanaka (1999) discuss the development of an artificial design assistant by combining rule-based inference, a genetic operator, and genetic case-based algorithms. The concept of a personalized assistant for early design is demonstrated using skeletal designs.

Kleban (2001) captures heuristic knowledge in an online computer system prototype called the Materials and Process Design Environment (MPDE). The MPDE contains Smart Process Advisors (SPA) that serve as "virtual manufacturing experts" for product designers. The MPDE contains three SPAs for material, near net shapes, and joining. The system theoretically provides the engineer with a candidate set of solutions for problems as well as organized manufacturing rules of thumb.

Kolb and Bailey (1993) utilize object-oriented modeling with constraint propagation to integrate design analysis codes with multidisciplinary design decision making. A prototype for flexible representation of objects for design optimization, FRODO, is discussed and some applications are presented.

Kumara and Kamarthi (1992) use adaptive resonance theory networks to organize families of design problems using functional requirements. Adaptive resonance networks identify learned design problems and their solutions to develop optimal design solutions. The research also compares adaptive resonance networks to k-mean clustering algorithms.

O'Sullivan (2002) presents a theoretical framework based on an interactive constraint-based approach to supporting the conceptual design process. A computational reasoning environment is coupled with constraint filtering to form the basis of an interactive early design tool.

Pallez et al. (2001) propose a framework that combines function to form mapping techniques with an intermediate specification model to create a collaborative conceptual design environment.

Parmee and Bonham (2000) develop a strategy for supporting conceptual design based on variable mutation cluster-oriented genetic algorithms (vmCOGAs). The technique is demonstrated through application on two-dimensional test functions.

Qiu et al. (2002) propose an evolutionary strategy to improve conceptual design based on an attribute encapsulation method. The method requires the combining of design features to general potential design concepts.

Rao and Lu (1993) propose inverse engineering as a means of facilitating iterative exploration of tradeoffs in the design space. Machine learning techniques are utilized to learn bi-directional models that can provide design support. The methodology is demonstrated using the design of diesel engines.

Roller (1989) proposes a design by features for high-level shape manipulations as a means for generating drawings in a faster more accurate way. Further, the approach is seen as the means to integrate computer aided design (CAD) systems with subsequent applications, like process planning. The research primarily formalizes the definition of features and demonstrates examples of advanced solid model design. The means of integrating the approach with subsequent applications is not explored.

Schroder and Jetter (2003) use the term “fuzzy front end” for the earliest stages of the new product development process. They apply psychological findings related to action regulation to the process of generating conceptual designs, and propose a framework for a management support system based on fuzzy cognitive mapping. The architecture and examples are presented at a very high-level, and one simple example is illustrated for wind turbine manufacturing. The potential benefits of the approach are discussed, along with the opportunities for future research to address the questions not yet answered with regard to the proposed concept. (Verganti’s work is referenced in this document.)

Simpson et al. (1995) present a conceptual framework that combined Design for Assembly (DFA) with a decision-based extension called Decision Support Problems (DSP). DSPs are abstracted DFA principles for use during conceptual design.

Smith and Sankaran (2003) apply a methodology for probabilistic multidisciplinary design optimization. Reliability analysis methods are demonstrated in a multidisciplinary system framework.

Sycara and Navinchandra (1992) explore the use of case-based reasoning to create a computerized Case-based Design Engineering Tool, CADET. The system attempts to use the physical attributes, function, and behavior of designs to retrieve candidates from a case database.

Wilcox and Wakayama (2003) discuss the use of commonality to minimize aircraft design costs. Commonality is used to simultaneously optimize designs across multiple aircraft, as opposed to just derivative aircraft. This type of approach has been used in automobile manufacturing for many years, but an extension into the arena of aircraft design has not been studied. The study shows that significant reductions in design time and ultimately total cost can be accomplished by defining commonalities between aircraft designs in general, not just derivatives.

Xu et al. (2002) present a conceptual NC configuration model based on cooperative multi-agents. Modularization is a fundamental building block of the system. Each module is a unique entity participating in design, and the product design process is accomplished by the cooperative work of agents. The prototype system is in the infancy of development.

Ye et al. (2000) use feature-based design and object-oriented representation to provide guidance on the hierarchical assembly of injection molded parts. The use of features allows the designer to work at a higher-level of abstraction and objects combine data structures and behaviors. Design for assembly (DFA) concepts are explored using the relationships between assembly objects, such as part-of (next assembly), fit (size), and limits of motion.

Yang et al. (2003) integrate Quality Function Deployment (QFD) with fuzzy set theory to create a fuzzy QFD methodology for producibility evaluation.

Zhang et al. (2001) develop a prototype knowledge-based system for conceptual design (KBCS). The prototype uses functional reasoning processes to match a production rule base to an object-oriented behavior base. Desired engineering requirements/functions are causally matched in order to define design solution starting points.

Zhao and Zhang (2002) study the use of extenics during the conceptual design phase of mechanical products. Extenics is a new artificial intelligence mathematical tool. The study applies extenics to a conceptual tool storage design problem. Comparisons are made to neural network and fuzzy logic approaches.

3.2.2 Group 2: Engineering Design Activity – Design Systems With Cost Emphasis

This group of research deals with the Engineering activity on the GPDP IDEF0 diagram Figure 2.5, and the design systems and trade studies mechanisms. The methodologies are stand-alone efforts within the Engineering activity, and do not require linkage to other existing activities or enterprise systems. The emphasis is on improvements to engineering design systems for use by the design engineer during the early design stages of product development. The primary goal of the research is to couple part design knowledge with cost information in order to facilitate better design decision making. Some use of manufacturing process data may be used, but the knowledge is in a system that is not directly linked to vendor or in-house capability databases.

Ayag (2005) discusses the use of the analytic hierarchy process (AHP) in combination with simulation techniques to evaluate design alternatives during conceptual design. A framework for AHP integrated simulation analysis and seven generic application steps are presented. A case study for a manufacturing system producing plastic injection molded parts for an auto-supplier is presented.

The manufacturing organization is analyzed, and operations data are broken down into groups by weight, lot size, common engineering materials, the types of molding machines used, machine capacity, assembly, and testing. A generic molding sequence is developed, and criteria are established as ease of manufacture, color, durability, and weight. A simulation procedure is then utilized to determine the potential matrix of conceptual design alternatives and associated costs. The resulting matrix of information provides sensitivity ranges that can assist a designer with decision making. For example, if concept X has a specified set of attributes, then it can be expected to cost 20% more than concept Y having a variation on attributes.

Ayag proposes that future work will entail creating a knowledge-based system that operates on pre-defined rules via a user interface. Fuzzy logic is also a possibility to add to the AHP approach.

Boothroyd (1994) utilizes the philosophy of Design for Manufacture and Assembly (DFMA) as the basis for early design decision making. DFMA time standards and knowledge bases are created to estimate assembly costs, detail part costs, and tooling costs without detail drawings. Case studies are used to discuss DFMA application successes with regard to part count reduction.

Butterfield et al. (2004) use a multidisciplinary approach to design a cascade box for a thrust reverser. Three different conceptual design configurations are analyzed using finite element analysis (FEA), computational fluid dynamics (CFD), and a SEER-DFM costing software package. After several design iterations, the researchers are able to make cost inferences related to the differing design features on each conceptual design configuration.

Choi et al. (2005) describe a computerized tool for estimating the cost of manufacturing composite parts. The system uses a Visual Basic for Applications (VBA) graphical user interface to input certain design features and key elements of the assembly process. Interfaces with CATIA V5, (Computer Aided Three-dimensional Interactive Application), extract geometric properties directly from electronic representations. A stand-alone Production Cost Analysis Database, (PCAD), generates a total cost estimate using first order velocity models.

Curran et al. (2005) discuss the use of genetic-causal cost modeling during the conceptual design of aircraft. The genetic makeup is inherited from the design definition, product nature, and process nature as organized into defined groupings. The causal makeup is characterized by drivers that are influenced by items such as weight, parts count, sizing, material selection, and other environmental factors. The methodology is demonstrated using engine nacelles examples. Linear regression is used to develop cost models based on the genetic-causal factors. The genetic aspect identifies weight, part count, and fastener count as significant cost identifiers. The causal aspect identified material, part fabrication processes, assembly, and procurement cost. The genetic-causal models provided better results than traditional weight driven parametrics.

Curran et al. (2006) present a methodology for modeling aircraft cost during the conceptual design phase using engine nacelles examples. The study selects a group of features known early in the design process, and then develops stand-alone cost models sensitive to these features. The selected features are weight, fan diameter, air wash area, and thrust. Actual data from prior nacelles manufacturing effort is broken into six manufacturing steps, and the cost drivers are used for linear regression modeling of cost. Other costs for raw materials, purchased parts, support, amortization, and “miscellaneous/other” are derived using actual data and factors. The modeling effort ascribed in the paper claims to achieve better results that just parametric approaches based on weight alone.

Giachetti (1997) proposes a set-based approach based on relational databases could be used to provide a ranked list of manufacturing process and material selection alternatives during early design. Material properties, process capabilities, and costs are represented in a relational database. Then, mathematical approaches, i.e., relational algebra, possibility theory, and trapezoidal fuzzy numbers, are used to produce a list of ranked solution alternatives.

Hsu and Woon (1998) present a thorough overview of current research in conceptual design products, and then discuss their interpretation of the best future research direction. Data mining, neural networks, genetic algorithms, and machine learning techniques are deemed to be promising. Future research direction proposals are the primary outcome of the study.

Johnson and Robinson (2005) discuss the process used to develop a conceptual design for the X-43D, a Mach 15 flight test vehicle. The study provides insights into how a baseline conceptual design and key technical issues are used in the development of a high-level project plan, including work breakdown structure (WBS) costs and key programmatic risks. It is not readily apparent how the results would be repeatable for another design configuration.

Kroll (1992) introduces a new approach for performing cost estimates to guide the design process through what is called Function Realization Cost (FRC). Instead of using features or processes to estimate cost, FRC utilizes functional allocations of cost. Specifically, data are categorized by four simple definitions and their associated arguments; FRC variables are function, form, context, and cost. Kroll claims that the strength of the approach lies within its simplicity. In some regards, the approach seems very similar to grouping data to develop parametric cost relationships. It is difficult to determine without more detail, and the proposed extensions discussed could not be found in the literature.

Oh et al. (1995) propose the use of constraint networks coupled with DFA principles to facilitate design decision making. A conceptual prototype, SPARK, is discussed.

Park and Khoshnevis (1993) describe an approach where real-time computer aided processing planning (RTCAPP) is coupled with precedence rules, process rules, machine rules, tool rules, manufacturing facts, and a cost evaluation module to produce real-time cost feedback to design engineers.

Rais-Rohani and Greenwood (1998) discuss the development of systems to be used by designers during the early design stages that are based on product and process coupling within a framework of integrated process and product development (IPPD) and multidisciplinary design optimization (MDO). The three-tier approach described in this paper describes a procedure by which product and process requirements coupled. A manufacturability analyzer examines key manufacturability compatibility factors. The concept of variable-complexity cost estimation (VCCE) is introduced to obtain a relative cost measure for trade studies. An enterprise model addresses factors related to non-manufacturing entities throughout the enterprise.

Rowell and Braun (1999) present a multidisciplinary conceptual design optimization framework and approaches, which uses a variety of computational approaches, including parameter, gradient-based, stochastic, and collaborative methods. Design to cost techniques are part of the conceptual design framework. The application examples are geared toward the development of space transportation systems.

Sandberg (2005) discusses how knowledge enabled engineering (KEE) can be used to improve overall manufacturability. KEE includes engineering design, knowledge based engineering (KBE), and related knowledge intensive tools, used in unison, in order to improve decision making during the concept phase. First, design and process knowledge is formalized into classes, properties, and rules. Next, a cost model is developed that is sensitive to the acquired knowledge in the formalized database. Lastly, once a design has been generated into a concept view, the user selects various manufacturing properties from a list, and the inputs generate a parametric cost value and/or producibility feedback. A prototype example of a flange design is presented.

Schlimbach and Mitschang (2006) develop a methodology for estimating the process time associated with thermoplastic composite tape placement using a combination of geometry, weight, and complexity. Complexity is further defined by the number of local reinforcements, fiber angles, machine axes, machine movability, and acceleration/deceleration. Once the cost model is defined, a variety of response surface procedures are used to study the possible combinations of factors and related cost.

Taleb-Bendiab (1993) presents a conceptual knowledge-based system called Concept Designer using a combination of design knowledge reuse and a heuristic costing function. Design concept reuse is based on reusing past cases, components, or concepts. Various Concept Designer system representations of proposed solutions are presented along with conceptual schematics.

Vollerthun (1998) discusses the development of an Integrated System Model (ISM) for use on the design of a Solar Probe spacecraft being studied at NASA’s Jet Propulsion Laboratory. The ISM combined three tools: 1) subsystem simulation tool, 2) cost estimating tool, and 3) effectiveness rating tool. First, a simulation tool models size (dimensioning/features) and performance of a proposed subsystem. Next, a cost accounting tool combines the dimensions with cost estimating relationships that match the Work Breakdown Structure. Finally, a tool predicts the effectiveness of the proposed design. The paper discusses how the ISM is used to identify the primary cost drivers of design.

Wall (2004) discusses model-based design within the context of space missions. Space missions are divided into four phases: 1) conceptual design, 2) formulation, 3) implementation, and 4) operations. In conceptual design, the determination of the existence of a feasible design is performed, a total cost is estimated within an accuracy of +/- 30%, and a realistic schedule is determined. The formulation phase involves engineering a buildable design. The implementation phase involves the fabrication, purchase, and test. Finally, the operations phase begins with the launch of the spacecraft.

Wall further asserts that model-based design has been used during conceptual design for many years, but the goal of extending these methods to the later phases of design has been obscure. In order to improve the ability to explore design trade spaces, it is necessary to develop connections between conceptual and detail design tools. In this article, a prototype system called MMPAT (Multmission Power Analysis Tool) is presented to illustrate how conceptual design tools can be linked to tools used in the formulation phase. The system utilizes a predetermined set of key user parameters and cost models to allow mission-wide trades. The article says that an operational version of the tool is in work, and that a full suite of models is planned for development, but no follow-up references were located.

3.2.3 Group 3: Engineering Design Activity - Logistics Engineering Emphasis

This group of research deals with the Engineering activity on the GPDP IDEF0 diagram in Figure 2.5 and the logistics plan control, trade studies, and IPT mechanisms. In particular, logistics engineering issues and related cost assessments during the early design stages are discussed. In general, logistics can be defined as the procurement, distribution, maintenance, and replacement of products, material, or personnel. The intended users are the design engineers and members of a concurrent engineering team. The efforts result in stand-alone systems that are not linked to other enterprise systems.

Smith and Knezevic (1996) discuss the concept of increasing quality and reducing overall product cost by focusing on supportability. Spares and support equipment estimation are highlighted.

Dowlatshahi (1999) proposes the use of Design for Logistics (DFL) along with a modeling approach for logistics called Bond Energy Algorithm (BEA). DFL is further broken down into four subgroups: logistics engineering, manufacturing logistics, design for packaging, and design for transportability. BEA is a clustering approach. The goal of BEA is to group design factors into Design Factor Families (DFF) and Module Families (MF). This allows designers to consider design factors common to a set of modules. Theoretical application examples are presented.

Wahl et al. (2001) discuss the effects of testing on logistics systems and cost. Testing is required for preventative maintenance and repair, and Design for Test (DFT) is a methodology to consider these logistics costs during design. The paper presents the prototype of a new tool called Systems Test (ST); a model based cost optimization tool.

3.2.4 Group 4: Engineering Activity – IPT Systems Emphasis

This group of research deals with the Engineering activity on the GPDP IDEF0 diagram in Figure 2.5. The mechanisms considered are the IPTs and legacy systems. The primary emphasis is on the re-design of processes, systems, and methodologies to support the collaboration of people in different disciplines and in different locations in the new product development process. Some of the literature is dedicated to the discussion of various theories to improve IPT product development decision making, while other research deals with a particular computer software only, without changing existing processes. Lastly, some of the research focuses on studies of how IPT members interact.

It is possible that a few of the conceptual approaches in this group of research could have application to other activities besides Engineering. However, it was not readily apparent whether the resulting systems were something other than stand-alone systems. Ongoing system linkages to activities downstream of Engineering are not fully explored or explained.

Austin et al. (2001) conduct an experimental workshop with multidisciplinary design professionals and mapped their progressions in decision making phases. The results are used to develop a preliminary framework for use in developing design activity models.

Barski et al. (2001) propose the use of group problem solving, conforming decision making, and simulation to develop decision support system (DSS) environments. The DSS technology would support manufacturing systems organization management for strategic planning and conceptual design. The frameworks of two prototype systems are discussed, MultiExpert and DIANA-11.

Carballo and Director (2001) apply constraint-based heuristics to collaborative design processes called active approach to design process management (ADPM). In order to evaluate ADPM, an evaluation environment called TeamSim is developed. Simulation results suggest that ADPM is a viable approach.

Chen and Liang (2000) propose the unification of the principles of virtual enterprise and concurrent engineering to define a new approach called Allied Concurrent Engineering (ACE). The authors present a conceptual system architecture that facilitates communication, control, and coordination of the multifunctional product development environment.

Huang and Gu (2006) describe the dynamic characteristics of the product development process, and attempt to model a product development process as a dynamic system with feedback. A fuzzy evaluation and design structure matrix (DSM) approach is illustrated. The results suggest how design constraints, design processes, and designer preferences can be optimized based on reorganization.

Huang et al. (2001) develop a prototype, web-based platform for pragmatic online project management information (POPIM). POPIM is designed to manage collaborative product development projects. POPIM provides a common workspace for multidisciplinary teams in different locations to use.

Huifen et al. (2003) present a model and conceptual architecture for a virtual enterprise system based on feature-based collaborative design. Features are regarded as the communication unit of the model and facilitates processing between multiple users at different places.

Hung and Adeli (1994) develop an artificial neural network environment, (ANNDE), using object-oriented backpropagation techniques. The integration of ANNDE with a knowledge-based expert system is presented as a viable means of improving the structural design process.

Kan et al. (2001) develop virtual reality-based collaborative environment (VRCE) using VNet, Java, and Virtual Reality Modeling Language (VRML) to demonstrate the potential for use in the collaborative design process of small companies. A theoretical case is used to illustrate the application of the system.

Lee et al. (2001) propose feature-based modeling as the means for integrating engineering and supporting activities. By using features in a wide range of applications, a web-enabled distributed collaborative environment would be possible.

Lee and Kelce (2003) develop a conceptual model of a new tool called Total Manufacturing Information System (TMIS), based on an integrated systems concept. Decision making is no longer sequential, but is instead, concurrent. The authors present the conceptual system architecture for the TMIS supported product development environment.

Leihn (2003) asserts that online collaboration as being the most important next step in improving the product development process. New internet-based technologies used in conjunction with XML (Extensible Markup Language) and J2EE (Java 2 Platform Enterprise Edition) are discussed.

Li et al. (1996) present a study that concentrates on automating the conceptual design process using heuristics and qualitative techniques. Specification libraries are created for a standard set of devices that cataloged function requirements, behavior, and qualitative descriptions.

Ma et al. (2002) discuss an approach to implement the architecture to support network-based conceptual design for geographically dispersed design teams. The approach is based on current CAD systems and the use of multi-modal technology, which integrates gesture, speech, and sketch surfaces with traditional interfaces.

Ma and Tong (2003) propose the use of associative feature modeling for concurrent engineering integration. An associative feature allows for a consistent set of data among users with different functional views.

Miller (2001) discusses the need for collaborative product definition management. Investment in collaborative software was stressed as being the primary means to connect physical and intellectual supply chains across the manufacturing enterprise.

Neff and Presley (2002) implement a prototype system called Concept Design Center (CDC). The software demonstrates how teams could theoretically solve concurrent engineering problems in a collaborative environment.

Qin et al. (2003) investigate virtual reality modeling language (VRML) design tools. In particular, the use of sketch and simulation design tools that are web-based and linked to behavioral simulation programs.

Reich et al. (1999) propose the use of n-dimensional information modeling (n-dim) to facilitate the development of Agile Design Information Systems (ADIS) for use in the Collaborative Product Design (CPD) environment. The conceptual system architecture is presented, along with a matrix of n-dim features matched to ADIS requirements.

Schut (2003) reviews the state of the art in E-Collaboration software tools. E-Collaboration is being used by some companies, but is not progressing as expected. The most successful implementation cases are reported for mature designs that have CAD files available for viewing.

Sky and Buchal (1999) develop an integrated conceptual product life cycle model within a virtual collaborative environment framework to support concurrent engineering. The major emphasis of the study is on the technologies, such as text-based chat, whiteboards, video conferencing, audio communication, and net meeting.

Sundar et al. (2001) present a framework for the facilitation of agile collaboration technology. The framework suggests not only a need for improved communication platforms, but that additional support is required to make certain that team members are being provided feedback on the product features, time to market, and cost within the communication environment.

Tay and Gu (2002) describe a function-based product model for conceptual design decision making support. Product information is represented in an object-oriented manner. Function-form mapping is used to correlate functional and physical domains. A prototype system is partially demonstrated.

Tolometti and Sanders (1998) propose a conceptual framework for implementing a collaborative enterprise environment (CEE) to support Air Force acquisition reform.

The paper presents a framework that supports enterprise level collaboration of multifunctional experts using a CEE, along with the conceptual system architecture called Decision Support and Resource Management System (DSRMS).

Wang and Chien (2003) present a conceptual prototype of a web-based group decision support system (GDSS). The system architecture is based on object-oriented and agent technologies. Two modules are demonstrated that use rule-based reasoning and Bayesian network-based reasoning. An example demonstrates how the system could be utilized to assist with a pricing decision.

Wang et al. (2002) present a state of the art review and future trends discussion of collaborative conceptual design systems. The authors conclude that knowledge management and reuse in design are the most important areas of research. Web-based and agent-based approaches are identified as dominant and enabling strategies. Developing a shared ontology is seen as the most difficult task.

Xu et al. (2001) propose a constraint-based distributed intelligent conceptual design environment system model as the means of managing computer supported collaborative conceptual design (CSCCD). Samples of the constraint-based distributive knowledge representation model are presented.

3.2.5 Group 5: Engineering and Planning Activities – Systems Integration Emphasis

This group of research deals primarily with the Engineering activity and the Planning activity on the GPDP IDEF0 diagrams Figure 2.5 and Figure 2.6, including planning systems, engineering systems, and IPT mechanisms. The primary emphasis is the interface between design engineering and process planning systems. The premise is that expert planning systems or planning knowledge-based support systems can help facilitate the link between CAD and CAM domains. Ultimately, the improvements will facilitate earlier and more effective decision making. The intended user is the manufacturing engineer, planning expert, or design engineer.

Allada and Agarwal (1996) propose the use of design feature relationships to formalize the process of determining machining operation sequencing. The paper defines a variety of negative and positive feature interactions, and then provides examples of IF-THEN statements to drive sequencing decisions.

Cutosky et al. (1993) assert that the most effective way to design products is to develop products concurrently with manufacturing plans. Their approach, process-oriented design, couples design and manufacturing features to generate process plans. Expert systems that emulate human design teams is discussed. On-going work on a prototype system, First Cut, is presented.

Feng and Song (2000) provide an overview of the various aspects of information modeling to integrate early design knowledge with process planning. An activity model for the conceptual design process is presented along with an object model for classes used in conceptual design. Standard interface specifications between design and process planning systems are discussed.

Hale et al. (2003) discuss the development of a prototype of a knowledge-based system that is capable of generating a process plan and costing of an aircraft engine using minimal design information. The system includes a common ontology, rules for generating a generic manufacturing sequence, and a comprehensive library of rules and algorithms for creating a parametric cost estimate. A great deal of progress was reported, but the amount of information required to make the system functional poses challenges.

Hayes and Wright (1989) develop a conceptual prototype system that is modeled primarily after a human planning process. Design features and subfeatures are defined for various part configurations. An expert system contains rules and guidance associated with features and subfeatures. Feature interactions are used to guide search the system to develop a viable process plan.

Kastelic et al. (1993) propose the use of relational databases of process parameters to drive computer-aided process planning (CAPP). The relational databases would contain numerical values of process parameters and be coupled with expert system data and various design feature libraries. The conceptual design and architecture of the proposed relational database approach is discussed.

Krause and Schlingheider (1995) discuss the use of knowledge-based software tools (KBST) to solve a variety of design and development problems. Their fundamental requirements for KBST are object-oriented programming, rule-based processing, and algorithmic knowledge. The planning task is theoretically accomplished by using features coupled with stored planning knowledge.

Matsushima et al. (1982) demonstrate how artificial intelligence techniques could provide design feedback and generate the optimum manufacturing sequence based on part features.

Molloy et al. (1993) explore the use of feature-based modeling to integrate Design for Assembly (DFA) and computer-aided process planning (CAPP) systems. The theoretical architecture of the envisioned system is presented.

Phillips et al. (1984) perform a preliminary investigation into the use of artificial intelligence techniques to develop a system to integrate CAD and planning knowledge to generate process plans. The theoretical system consisted of three parts, a planning expert system, a part database, and a process database. Part features are used to couple the three subsystems and generate process plans.

Pratt (1984) proposes the use of automatic feature recognition as a means to automating process planning. Simple machining features from a particular type of boundary representation are utilized.

3.2.6 Group 6: Business Management, Engineering, and/or Factory Management Activities - High-Level Cost Estimation Tasks Without Process Plan Generation Emphasis

This group of research deals with cost estimating tasks potentially performed within the Business Management, Engineering, and/or Factory Management activities on the GPDP IDEF0 diagrams, Figures 2.4 and 2.5. The mechanisms considered are cost models, design systems, trade studies, and cost studies. This group of research deals with the development of cost estimating tools that can be utilized during early product development, and they perform with high-level information. The intended users are engineers and cost analysts. The tools do not utilize a “best guess,” or intermediate, process plan approach to establish an estimating baseline and discrete tooling requirements and scheduling considerations are not considered. (An intermediate plan would occur before a detailed final process plan was developed.) Hence, there is no linkage to the activities downstream of the engineering activity. For example, the design feature of “hole” could be estimated, but the cost information would not be sensitive to where the hole was drilled in the factory, what type of drilling process was used, or the specific tooling costs and scheduling impacts of using one process versus another.

Asiedu and Gu (1998) propose that cost should be added to the “Design for X” realm. In past undertakings, the “X” has stood for assembly, manufacturing, producibility, etc., and while these approaches reduced cost, the design criteria they utilize is not cost.

Bode (2000) demonstrates the use of neural networks for cost estimating using a personal computer development case as a pilot application. The cost estimating performance is compared to linear and non-linear parametric regression. Neural networks are deemed better when fewer cost drivers are known. The desired parameters are cost drivers of five or six, and at least 50 to 100 past cases available.

Chen and Jang-Jong (1999) combine design rules from DFM and DFA with feature-based cost value to develop a prototype online cost evaluation tool for injection molding.

Creese and Patrawala (1998) provide a thorough review of feature-based cost modeling efforts published in the 1950s to make the point that feature-based cost modeling is not a new idea. Then, they proceed to develop a cost approach that uses elements of feature-based cost and parametric cost modeling.

Curran et al. (2001) propose using a multidisciplinary IPPD framework in conjunction with historical cost estimating relationships (CERs) to improve integrated aerospace design. Key IPDD drivers are identified using QFD and DFMA principles, and then correlated to appropriate CERs. Overall performance is measured by using direct operating cost (DOC).

Greenwood (2003) defines key processes that provide the foundation for the development of an Insitu Design Cost Trades (IDCT) tool and future design/cost decision support systems, including cost estimation, requirements engineering, and product design. This paper is one of the few that considers risk and uncertainty, including a Monte Carlo simulation engine. A cost analysis decision support system architecture and the results of a working prototype of the IDCT tool are presented.

Jahan-Shahi et al. (1999) propose using fuzzy sets and probability distributions within an activity based costing (ABC) framework to address the problem of uncertainty in estimating the cost of flat plate processing. Mamdani-style fuzzy inferences are used to develop a simple, rule-based fuzzy model. Input variables, such as plate size and labor type facilitated the use of the ABC costing framework.

Jung (2002) uses feature-based methods to develop a conceptual prototype system for estimation of the metal removal time for machined parts that is subsequently used in cost estimating models. A metal cutting classification scheme defines features as rotational, prismatic, slab, and revolving. Equations are used to estimate the processing time required by feature. In addition, supplementary inputs for machine type, number of machines, tools, cutter type, number of cutters, cutter ID numbers, material type, material specification, material dimensions, and batch size.

LaMont and Benjamin (1995) introduce a new costing methodology for modular spacecraft called Dynamic Integrate Cost and Engineering (DICE). Existing engineering models for selected spacecraft subsystems are appended with hardware and cost databases to create a new model to output engineering analytical parameters like torque and momentum with power, weight, and cost.

Park et al. (2002) introduce the approximate product life cycle costing (APLCC) method for conceptual product design cost estimating. Significant product attributes are determined using statistical analysis. Neural network algorithms are applied using the product attributes as inputs and the APLCC as outputs. Trained learning algorithms for known characteristics of past products provide the estimation of APLCC for new product designs. A conceptual methodology is presented.

Rehmann and Guenov (1998) present a conceptual methodology for modeling manufacturing costs at conceptual design based on the blackboard framework of problem solving. The blackboard framework integrates case-based and rule-based reasoning to create a new, hybrid knowledge-based adaptation approach. An overview of the proposed architecture is presented, and prototype was reported to be under development.

Wierda (1990) publishes a survey of design-oriented costing methodologies. The most widely used approaches included some type of design rules, manufacturability information, and features.

Xue and Dong (1993) propose a methodology for automated concurrent design based on combining tolerance, feature, and cost models. The conceptual system utilizes feature-based reasoning, and knowledge and data are stored in clusters. A framework of the prototype system is presented.

Yeo et al. (1997) develop and apply cost-tolerance relationships for non-traditional machining processes, in particular, electrical discharge wire machining and laser beam machining. Four mathematical models are developed from empirical data, and based on fitting errors; a third degree polynomial model gives the best fit.

3.2.7 Group 7: Business Management, Engineering, Factory Management Activities, and Planning Activities - Detail-Level Cost Estimating Tasks With Process Plan Generation

This group of research deals with cost estimating tasks potentially performed within the Business Management, Engineering and/or Factory Management activities on the GPDP IDEF0 diagrams in Figures 2.4 and 2.5 in conjunction with knowledge that resides in the planning activity on Figure 2.6. The mechanisms considered are legacy systems, cost models, trade studies, cost studies, the IPTs, planning experts, and planning systems. The emphasis of this research is on the development of information systems that can be utilized during early design that have systemic linkages to detailed (lower-level) information. The tools utilize an intermediate process plan approach to establish a detailed information baseline. Hence, there is potential for linkage to activities downstream of the planning activity, even though it is not explored.

The approaches in this group of research highlight methodologies to integrate design, planning, and cost estimating information for use during the early stages of product development. In most cases, the design information is used to generate an intermediate process plan, and then the process plan information is used to develop cost estimates. In some articles, the primary purpose is to demonstrate a conceptual planning system, while cost estimating is secondary. The tone of the articles depends on the emphasis of the author(s). The intended user varies between the design engineer, manufacturing engineer, the cost engineer/analyst, or a multifunctional team.

Abdalla and Knight (1994) present a prototype system that combines the use of three components, a CAD automated feature recognition, a manufacturing facility expert, and a product features expert. Rule-based reasoning and object-oriented programming are used to develop the interface between the components. Features from CAD are recognized and expert systems create a process plan and cost estimates.

Brinke et al. (2000) propose a structure based on the Manufacturing Engineering Reference Model (MERM) for defining products and product characteristics that relate four cost drivers: geometry, material, processes, and production planning. The system queries historic databases and makes appropriate matches based on various elements, relations, and attributes. A viable process plan is generated and costs are estimated.

Evans et al. (1998) develop a framework for using process-oriented cost estimating as the basis for manufacturing process flow simulation and analysis. A viable process planning sequence is developed from previous experience or published materials. Processes are broken down into elemental details, and then customized parametric process algorithms are used to estimate the cost. An Organic Matrix Composite (OMC) material example is overviewed. (OMC is an advanced material for which little historical data is available.)

Feng (2005) continues prior research related to integrating conceptual engineering information with process planning. In this research, the use of web-based intelligent software agents is discussed. A prototype platform is presented where the user inputs a variety of details to generate preliminary process planning. Future work includes more exploration of design factors in order to develop better relationships between design factors and process selection and the ability to perform complex cost estimating tasks.

Feng and Zhang (1999) describe a conceptual process planning (CPP) prototype system that is integrated with a conceptual design system. The system integrates conceptual design and process planning in order to estimate cost. The integration uses engineering requirements, function, configuration, features, tolerance requirements, quantity, and delivery date.

Ferrelrinha et al. (1993) outline a knowledge-based expert system HKB. (German: <u>H</u>erstell-<u>K</u>osten-<u>B</u>erechnung.) The components of HKB are design, production planning, and tendering. (Tendering includes evaluation of potential bidders, bidder selection, solicitation, evaluation, and award.) The three modules of the software system are rule-based and rely on knowledge stored in tables, symbol catalogs, and process libraries. Part features and other information are input, a production plan is generated, and a cost estimate is tendered. ("Tendered" is used in the context that sales people are utilizing the system. It is not a common term in the United States, but different forms of "tender" are used throughout this article, which was published in Canada.) An overview of one example is presented.

Geiger and Dilts (1996) develop a conceptual model and partially working prototype to demonstrate automated design to cost. The conceptual methodology uses part features and group technology to develop an interim process plan. Activity based costing is used to organize cost accounting data into a format that will be sensitive to process costing.

Han et al. (2001) propose a conceptual approach for integrating part features, process planning, and manufacturing process cost. Hint-based reasoning (HBR) and integrated feature finder (IF2) are used to integrate CAD data with machining sequence knowledge. Cost equations are used to generate cost estimates based on the anticipated machining sequence developed from process planning knowledge.

Khoshnevis et al. (1994) propose an architecture for a cost based system referred to as real time computer aided process planning, (RTCAPP). A knowledge-based hierarchical planning scheme uses multi-bank rule matching to generate interim process planning. Cost estimation is performed using feature-based and equation-based approaches that are linked to processes.

Liebl and Hoehne (1999) describe a procedure for determining costs concurrently with design using a feature-based CAD system. The feature-based cost analysis modules generate a viable process plan from CAD system design features and provide cost calculations, comparisons, and forecasts.

Lukibanov et al. (2000) develop a conceptual process planning system, Socharis, for polymer composites manufacturing planning. DFM knowledge is translated into a conceptual process plan using various problem-solving modules using features, shape, joining, and part data. The refining module uses cost to develop ranked manufacturing plans.

Ou-Yang and Lin (1997) present a framework for estimating early manufacturing cost using a feature-based approach. Features are used to develop the process sequence and projected cost. The framework includes, but is not limited to, a feature library, a part database, feature-based CAD tools, feature manufacturing times, feature manufacturability rules, feature specifications file, machine specifications file, and manufacturing feature cost file. The approach requires that manufacturing and engineering data be retrievable in a feature-based format.

Sharma and Gao (2002) describe a feature-based conceptual design system (FBCDS) for use in progressive design and manufacturing evaluation. The system uses a feature-based approach to generate an interim process plan. An embedded cost system provides the cost of iterative designs.

Shehab and Abdalla (2001) propose a system for manufacturing cost modeling to support a concurrent engineering environment. Feature-based modeling is used in conjunction with feature-based knowledge bases for machines, production rules, machining times, etc., to generate a process plan. Cost algorithms, heuristics, and fuzzy logic are used to generate cost estimates and analysis of uncertainty. Some features of a socket are used to generate cost for a pocket, hole, and slot.

Shing (1999) develops a spreadsheet-based program to rapidly estimate the manufacturing costs of molded part designs. Preliminary concept sketches provide the design input. Features and design attributes are matched to tolerances and production rules in order to generate a process plan. Costs are calculated using a series of equations and costs sensitive to features and design attributes.

Tseng and Jiang (2000) develop an activity-based cost analysis methodology to use in conjunction with feature-based design and feature-based planning. The framework assumes the existence of feature-based design and feature-based process planning systems. The contribution of the research is the proposed methodology to incorporate activity-based cost analysis.

Wei and Egbelu (2000) propose a framework for estimating machining manufacturing cost using "And/Or tree" representation and decomposed removal volume (DRV). The input for the framework comes from an "And/Or tree" graph, then DRV unit cost data are used to generate the process plan routing, and the total manufacturing cost.

3.2.8 Group 8: Business Management, Engineering, Factory Management, and Planning Activities -Detail-Level Cost Estimating and Scheduling Tasks

This group of research deals with the Business Management, Engineering, Factory Management system, and Planning activities on the GPDP IDEF0 diagrams, Figures 2.4, 2.5, and 2.6. The mechanisms considered are cost models, legacy systems, trade studies, cost studies, schedule models, scheduling simulations, planning experts, and the IPT.

The approaches in this group focus on the integration of design, work instructions, cost estimating, and scheduling systems information. This research recognizes that the best way to improve product development is to model it as a network of interconnected activities. The literature in this group discusses methodologies that consider scheduling decisions concurrently with other decision making, particularly design and cost.

The number of articles in this group of research is small, but they begin to more closely emulate (imitate) what takes place in the real world. Scheduling is most often a key factor in product development decision making, and hence, should be systematically considered.

For example, the schedule sometimes causes a design to be fabricated using NC machining, when in actuality, the "low cost" decision using traditional estimating methods is a sheet metal design. When the makespan of a design is on the critical path, it becomes increasingly difficult to do trade studies. Intuitively, it is known that "time is money," but it is difficult to estimate and trade program schedule performance against cost performance. In addition, the timing of tasks and associated expenditures are necessary building blocks of project plans, capacity analysis, rate-tooling studies, financial forecasts, and many other management systems/tools.

Browning and Eppinger (2002) integrate several product development processes into a single model, and then analyze changes using simulation. Outputs include cost and schedule outcome distributions. Alternative process architectures are compared. The authors asserted that in order to increase efficiency and predictability in the product development processes the entire process needs to be modeled as a network of activities that exchange deliverables. Design delivers a drawing, planning delivers work instructions, estimating delivers projections of process cost, scheduling provides estimates of the timing of the tasks, etc. Effective trade studies should be done in a manner than consider the interconnection of deliverables, especially cost and schedule risk.

Mosher (1999) develops a prototype tool for conceptual spacecraft design, the spacecraft concept optimization and utility tool (SCOUT), which couples design information to other criteria of the trade study process. Genetic algorithm optimization is used to demonstrate the potential to use SCOUT in the cost and schedule trade selection process.

Shobrys and White (2000) assert that design, planning, scheduling, estimating, and control systems must be integrated in order for companies to make significant improvements in internal process efficiencies. Proactive integration, the removal of information silos, and designing new work processes that integrate multiple traditional functions are seen as the means for improving traditional approaches. The authors provide examples of how multidisciplinary workers and processes provided increased efficiencies.

Murman et al. (2000) assert that value is a function of performance, cost, and time. In order for aircraft manufacturing to be better, faster, and cheaper, (BFC), then the elements of value must be concurrently considering as a part of decision making processes. The authors demonstrate how key characteristics coupled with relative probabilities could be used to project cost and schedule decisions making solution spaces. The result is an optimized value function for BFC results.

3.2.9 Group 9: All Enterprise Activities – Knowledge Reuse Emphasis

This group of research deals with the all of the enterprise activities shown on the GPDP IDEF0 diagrams, Figures 2.4, 2.5, 2.6, and 2.7. The emphasis is on linking the mechanisms used prior to engineering release with those mechanisms used to created deliverables and monitor performance after the engineering design is released. In addition, the lessons learned controls in various activities are linked to facilitate knowledge reuse and enterprise level learning.

The approaches and methodologies take a “bigger picture” approach in how they deal with product development decision making. The goal is to create fully integrated systems that are geared toward capturing organizational knowledge and learning to be reused seamlessly within all enterprise activities. The downside to this research is that it is primarily still at the conceptual level.

Liang and O'Grady (2002) couple object-oriented formalism with feature-based engineering principles in order to achieve the goal of knowledge reusability in the situation where participants are geographically separated could be best facilitated by coupling object-oriented formalism with feature-based engineering principles. Their approach is called feature-based distributed concurrent engineering, (FBDCE). The conceptual framework for the architecture, process model, and implementation are presented.

Richards (2000) presents a user-centered approach for building knowledge-based systems that incorporated knowledge reuse. The knowledge acquisition (KA) technique is used in conjunction with ripple-down rules (RDR) to develop a knowledge-based system (KBS) prototype that will allow users to access knowledge in a variety of ways. This approach is broader than the traditional method of trying to build a KBS to emulate one, pre-defined expert.

Verganti (1998, chapter 11) proposes the use of reciprocal interdependencies and feedforward planning to improve decision making during conceptual design. General frameworks describing information reuse possibilities are presented in the context of teaming. The research describes how information from past product development efforts can be used in conjunction with anticipated manufacturing constraints to facilitate design concept generation and related decision making. (Chapter 1 provides an in-depth discussion of Verganti's work and it is not reiterated in detail here.)

Xiong (2003) takes a very high-level approach to discussing global manufacturing by using conceptual design, and begins with human society, manufacturing system, and natural environment. Then, he provides the frameworks for the forming process of a conceptual design system and a product conceptual design system. The article emphasizes the significance of the "factor of man" and society in developing a conceptual design system (CDS) where knowledge is effectively reused and continuously renewed. Instead of promoting the progress of computers, knowledge renewal and intelligent networks need to work to educate all actors in the conceptual design process. The renewal of knowledge of the workers should be viewed as one of the critical components of competitive advantage. In addition, multi-media technologies and training in multiple disciplines and theories should be viewed as critical to the global manufacturing system of the future. The paper claims that information will flow seamlessly throughout the enterprise, and the organizational barriers will dissolve when man, machine, and environment are viewed as a whole system.

Xu et al. (2007) present a theoretical decision support system for product design in a concurrent engineering environment. Fuzzy numbers and fuzzy line segments are used to support decision making during multi-stage evaluation. Unlike the other members of the group, this work does not emphasize knowledge reuse, and is geared toward using multi-stage fuzzy logic to organize abstractions.

3.3 Synopsis of Literature Review Findings

The majority of the research dealing with the product development process and related decision making deals with the engineering activity on the IDEF0 diagram and the activities that take places prior to design release, i.e., Groups 1 through 4. While there is often the recognition of the need to use information that resides in other activities, the resulting solution normally creates a stand-alone methodology or prototype that is not integrated with other existing activities on the IDEF0 diagram of the product development process.

Cost estimating and trade studies are emphasized in the majority of the research. Cost related techniques are discussed in Groups 2, 6, 7, and 8. Many techniques are reviewed, but the ones utilizing information that is linked or linkable to the process plan hold the greatest promise. In general, IPT members prefer to work with information that "looks like" what they are used to seeing in the production environment.

The Planning activity is where engineering information is translated into a critical piece of manufacturing control data that will follow a part or tool throughout its life on the shop floor -- the work instructions. Hence, the research found in Groups 5, 7, and 8 provide good starting points for integrating the activities that occur after design release with activities that take place prior to design release.

As more activities are considered in conjunction with the Engineering activity, the amount of available research becomes less and less. The increasing complexity makes the presentation and demonstration of methodologies equally complex and time consuming. The research in Group 8 is the only place where multiple activities are considered in conjunction with cost and schedule. As asserted by Verganti, most of the published literature does not reflect the task complexities involved with teaming and early design decision making.

A small percentage of the research takes a "bigger picture" view of the product development process. It focuses on how best to collect data and format knowledge for reuse throughout the enterprise. Knowledge as it exists today is housed in various formats and spread throughout the activities, and in most cases it is only formatted for the next user in the product development sequence. The needed improvement is to create an approach that allows for seamless information flow across all activities.

3.4 Summary and Conclusions

For many years, researchers have been working on approaches that consider the product development process within the context of one activity or a group of activities, and these approaches have not yet yielded methodologies and frameworks with industry-wide acceptance. It is apparent that there is a need for continued research related to manufacturing enterprise product development process improvement.

The GPDP approach and associated IDEF0 diagrams utilized by this research offer new perspectives not represented in the literature. These perspectives coupled with the insights gleaned from the literature review serve as a good starting point for further research.

Based on the literature review efforts, the area in most need of further research is found to be Group 9. Group 9 seeks to integrate all the activities within the product development process, and it emphasizes knowledge reuse. Intuitively, it stands to reason that in order to capitalize on the theories related to concurrent engineering, life cycle management, and virtual enterprise that Group 9 holds the greatest promise. In the long run, methodologies, frameworks, and approaches that do not concurrently consider all of the activities in the process flow diagram are likely to yield localized, suboptimal results.

Among the promising efforts identified in Group 9, the ideas of Roberto Verganti (1998, chapter 11) are selected for further study and extension by this research. The Verganti approach involves managing reciprocal interdependencies using feedforward planning concepts.

CHAPTER IV

RIM CONCEPTS AND THE PRODUCT DEVELOPMENT LIFE CYCLE

In this chapter, some of the more commonly held views of the product development life cycle are discussed in the context of reciprocal interdependencies management (RIM). Where appropriate, relevant assertions are offered in the context of aircraft manufacturing.

In Chapter 1, reciprocal interdependencies are defined as the knowledge links between activities or entities. Reciprocal interdependencies represent the information exchange that takes place between activities/entities in order to solve a problem (or, address a question) during the product development life cycle. Feedforward planning is a proactive approach to managing reciprocal interdependencies, and commonality and selective anticipation are strategies that are utilized within the context of feedforward planning.

There are several figures that are referenced in slightly different formats in a great deal of literature that speak to the problems related to the product development process. For the discussion that follows, the information from two different authors was combined to develop Figure 4.1. (Chapman, 2004; Kirby, 2001.) Figure 4.1 illustrates the following four factors.

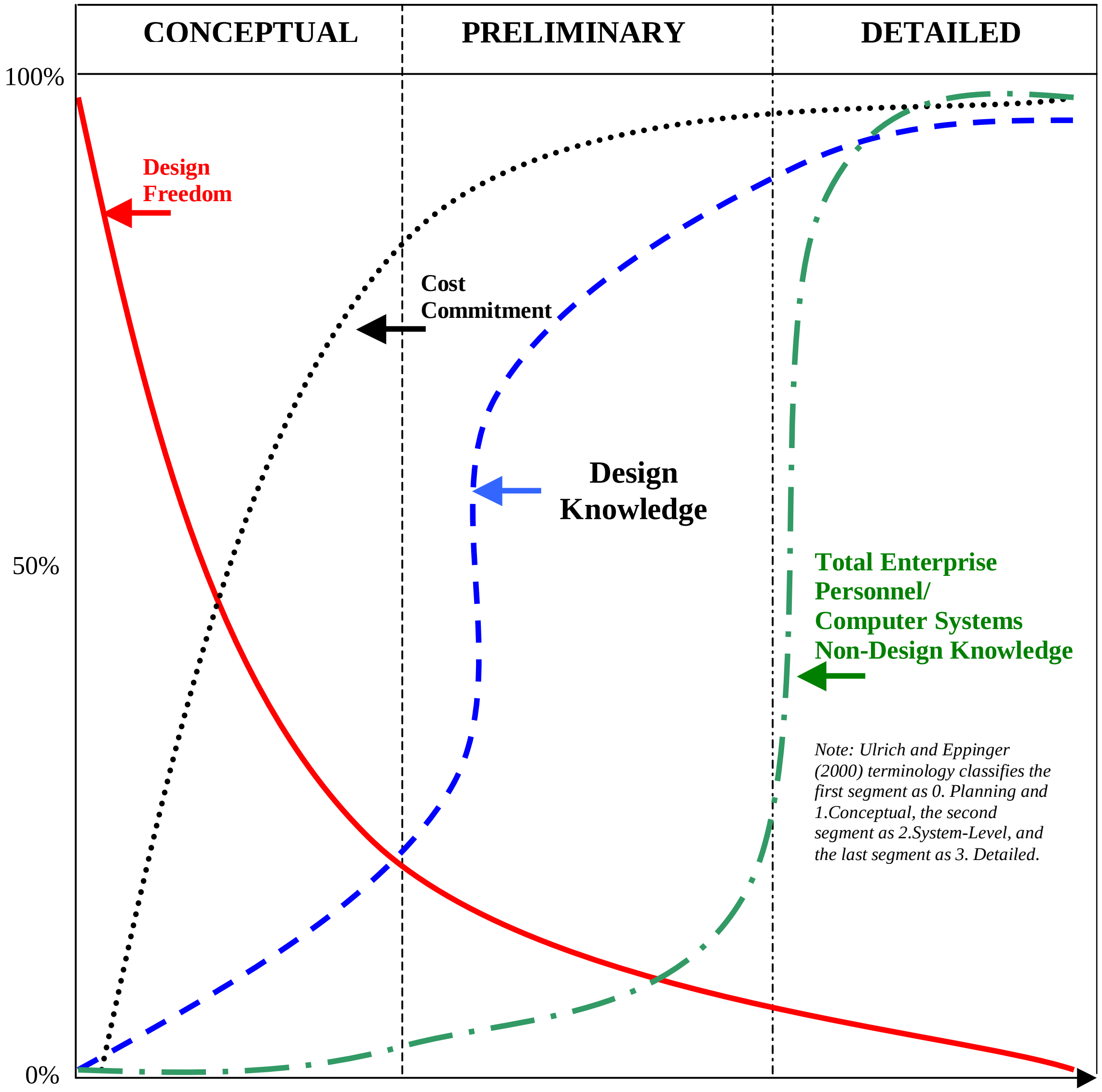
- Design freedom (the ability to act on information and make changes to the design)

- Cost commitment (the majority of total cost is committed early on, and is nearly the inverse of design freedom)

- Design knowledge (design information availability)

- Total personnel assigned (approximately 1% of the total employees during the conceptual design; an additional 9% are added during the preliminary design phase; the remaining 90% are added during the detail design phase, for a total of 100%; since the majority of early team personnel are designers, there is a correlation to non-design knowledge)

Since these types of figures are widely used in textbooks and journal articles, Figure 4.1 provides a good high-level starting point for considering the potential implications of RIM in aircraft manufacturing. In the sections that follow, Verganti's ideas related to RIM are discussed within the context of the four factors on Figure 4.1.



Note: Ulrich and Eppinger (2000) terminology classifies the first segment as 0. Planning and 1.Conceptual, the second segment as 2.System-Level, and the last segment as 3. Detailed.

Figure 4.1 Factors Related to Product Development Decision Making During Conceptual, Preliminary, and Detail Design Phases

4.1 Design Freedom and "Cost Commitment" Curves

Figure 4.1 illustrates that significant reciprocal interdependencies exist between "design freedom" and "cost commitment." These curves convey that "the design process" follows a pattern and the corresponding "cost commitment" follows a nearly inverse pattern. The figure conveys that once a design starts down a particular path toward completion, it quickly eliminates significant portions of the potential solution space. Similarly, even though the "cost commitment" for the design is not yet fully defined with regard to management of cost, i.e., "what, when, how, and how much", it has nonetheless reciprocally been established. The critical aspect of these two curves is that they both "flatten out" during the conceptual design phase, which leaves little room for change in subsequent design phases. Hence, the common assertion referenced in Chapter 1 is supported by these curves, in that, between 70-80% of the total cost of a product is established during the conceptual design phase.

The patterns of "design freedom" and "cost commitment" can be discussed with the context of Verganti's feedforward planning strategy, "selective anticipation."

> *"Selective anticipation consists of anticipating only a limited amount of information that allows one to verify the coherence between the product concept and the future constraints. Dedicating the most attention on a few critical areas."*

If the enterprise develops information management and approaches with the idea of predicting the patterns related to "design freedom" and "cost commitment," then it will take important steps toward better management of the reciprocal interdependencies that exist between the two. The obvious deliverables related to these sources of information to be managed are the "design representations" and the "cost estimates."

Since the curves on Figure 4.1 do not provide insights with respect to where this type of information comes from, the GPDP IDEF0 diagrams provide better insights with regard to applying RIM concepts. The IDEF0 diagrams from Chapter 2 support the assertion that activity with the most influence over the design is Engineering, however, the “cost estimates” aspects are not as clearly traceable, which is discussed in the next section.

4.2 Cost Commitment (Cost Estimates)

The technical descriptions of “cost commitment” are linked to the various definitions of cost and the analytical methods used to estimate cost. The GPDP IDEF0 diagrams from Chapter 2 show that systems and personnel concerned with “cost” are located in four activities, Business Management, Engineering, Factory Management (before release), and Factory Management (after release). Clearly, significant reciprocal interdependencies exist, and therefore, opportunities to manage them more effectively exist. RIM strategies of commonality and selective anticipation have implications at a global level, in that, these users should have tools and processes that are developed using commonality and methodologies applied should recognize selective anticipation in the assignment of cost drivers.

However, at this point a conflict between the IDEF0 diagrams and Figure 4.1 occurs for aircraft manufacturing in the defense industry, as well as any other industry that has to agree upon a price to the customer in advance of the actual design effort. The Business Management activity controls the contractual price (Price = Cost + Profit) quoted to the customer. In many industries, price quoting takes place after design and manufacture of a product. It is easily understood that the greatest amount of “cost/price flexibility” (ease of change) exists before the price is quoted to, and agreed upon, by the enterprise and the customer. While other analyses related to “cost” are performed later, some of the most important cost-related analyses in aircraft manufacturing happen much earlier than the typical industry/enterprise. Once the price is agreed upon, an associated "cost commitment" has been made to the customer, and this is the value that will be used to judge success or failure.

When one studies the "cost commitment" curve on Figure 4.1, it is difficult to correlate the "cost commitment" by Business Management in the aircraft industry to the "cost commitment" curve on this diagram. It seems the typical "cost commitment" curve found in the literature is missing something, or that some other representation of total cost should be added to the diagram.

Figure 4.1 illustrates that 80% of the technical aspects of cost are established during the conceptual design phase, but it does not appear to address how costs are actually developed and managed. While it is good information to understand, it seems to overemphasize the role of the technical engineering information and underemphasize the role of cost forecasting and management related decision making. Even a perfect design will not by itself lead to an optimal total cost if the endeavor is improperly managed or the original estimates of "cost commitment" are unrealistic and unrealizable.

In order to manage reciprocal interdependencies, an enterprise has to recognize their existence, and it appears that important reciprocal interdependencies related to management decisions that effect total cost commitment are missing from Figure 4.1

Tremendous advances have been made in the last 30 years with regard to managing technical engineering information, yet cost and schedule overruns continue to increase instead of decrease in the defense industry. (Swank, 2000.) This leads one to conclude that studying the reciprocal interdependences that exist between the Business Management activity and the Engineering activity and understand how they affect "cost commitment" is worthwhile. Though it is difficult to know what the real shape of the "cost commitment" line on Figure 4.1 should be for aircraft manufacturing, RIM has something to offer with regard to the investigation.

4.3 Design Knowledge and Total Enterprise Effort

Another interesting aspect to Figure 4.1 is the implication that "design knowledge" starts at zero percent. It is difficult to understand when the situation exists that design knowledge truly starts at zero percent. In actuality, it is highly likely that reciprocal interdependencies exist between past design efforts and the current design effort, and that RIM concepts of commonality and selective anticipation are applicable. However, the curves on Figure 4.1 do not offer any insights.

The S-curve for "design knowledge" looks more like an illustration of engineering drawing releases, which is based on a deliverable instead of "design knowledge," though published works do not go into this level of detail with regard to how the shape of the curve was derived. Again, it is difficult to envision how the reciprocal interdependencies between past design efforts and current design efforts change the shape of the "design knowledge" curve on Figure 4.1, they nonetheless exist. In this instance, a starting point to managing reciprocal interdependencies more effectively is the recognition that they exist and the application of feedforward planning strategies (commonality and selective anticipation) as discussed in Chapter 1.

As in previous discussions related to "design knowledge," the "non-design knowledge" is probably does not start at zero percent. "Non-design knowledge" is available from past endeavors if it is properly categorized using commonality. Similarly, "design knowledge" is available that these "non-design" users can apply to make inferences about their tasks earlier in the product development process if they use selective anticipation. This is another example of how RIM strategies can be applied to rethink the application of "non-design" effort. If more efficient ways of utilizing "non-design" effort are identified, then one would expect the "non-design knowledge" curve to move closer to the "design knowledge" curve, and for it to start somewhere further from zero.

4.4 Conclusions Related to Figure 4.1

Once reciprocal interdependencies are recognized as existing, then the RIM strategies of commonality and selective anticipation have the potential to be used to alter the shapes of curves like those in Figure 4.1. Though it is difficult to determine what the shapes in the future will actually be, the application of RIM strategies are expected to add a new cost commitment curve based on management, move the starting points of the curves away from zero, and perhaps move the curves closer together in some fashion.

4.5 IDEF0 Diagram Relationships and RIM Concepts

While illustrations similar to Figure 4.1 are useful, when one tries to apply them to defining problems and solutions, they do not provide enough information about the underlying problems. In addition, these figures seem to overemphasize the role of engineering information in decision making and underemphasize how the information is being used to manage the enterprise. The relationships presented in the generic product development process IDEF0 diagrams from Chapter 2 offer better insights into how information is exchanged, the problems that exist, and potential solutions. An example is presented in the discussed in the paragraphs that follow.

The Factory Management (after release) activity controls how estimates of labor and schedule are used to manage the execution of the manufacture of tools and parts. The estimating procedures for labor and schedule requirements are part of a manufacturing execution system (MES) that has limited flexibility. Because of factors such as floor space, equipment, and the number of personnel that can actually be effectively assigned to a particular job, these estimates of cost and schedule requirements are meant to be representative of what is needed to achieve the "should cost" for a product within established parameters.

It is important to note that no matter what any individual within another activity may have estimated with regard to manufacturing hours and schedule requirements, it plays no role in what is loaded for shop floor control via the MES. The MES work measurement system provides the estimate of the hours needed to do a job, and the MES scheduling system determines when these hours are to be earned/accomplished. Even if the scheduling dates are moved around, the total estimated hours (should cost) for the job is not changed. The actual hours charged and the earned hours to the baseline are what changes.

However, the "cost performance" of the job is determined by how well the information in the MES matches budget established during the original bidding process. If the original budget and SOW information provided by the Business Management activity led to the decision to hire too many personnel, then the result is poor performance and associated cost overruns. No matter what the work measurement system predicts jobs "should cost," once workers are hired, they have to charge to the work available in a particular area until they are laid off or moved to another area that has work. If the budget and SOW information provided by Business Management led to hiring too few personnel or the wrong mix of personnel (e.g. machinists were hired but painters were needed), then the result is poor performance and cost overruns.

Hence, the observation is made that the enterprise should utilize information found within the MES as quickly as possible in its estimating procedures, and it should maintain traceability to a defined baseline of information. Referring back to the IDEF0 diagrams in Chapter 2 and Figure 3.1 in Chapter 3, if an approach is developed to emulate the logic used within the Factory Management activity (i.e., activity 4) after design release to feedforward knowledge to activities engaged in decision making before design release using RIM strategies, (i.e., activities 1, 2, and 3), then the feedforward of knowledge offers the potential to improve conceptual design decision making.

4.6 Summary

In this chapter, high-level discussions of RIM concepts are offered in the context of figures commonly used in the literature and then another level of detail is discussed using the IDEF0 diagrams in Chapter 2. Recall the discussion of feedforward planning presented in Chapter 1. Feedforward planning is a proactive approach to managing reciprocal interdependencies. The future constraints and opportunities that exist are anticipated and accounted for as early as possible at the level of detail required for effective decision making. A great deal of common enterprise knowledge related to future constraints and opportunities is housed within Activities 4 through 8 (i.e., the IDEF0 diagrams in Figures 2.5-2.7) that are completed once a design is released.

The discussions in this chapter provide insights into how RIM concepts are used to rethink commonly held views of the product development life cycle. Referring to Figure 3.1, information housed on the "right side" (after design release activities) of the GPDP diagrams has feedforward planning potential to create knowledge for use by earlier activities on the "left side" (before design release activities) of the GPDP diagrams. RIM concepts of commonality and selective anticipation can be used to organize information from past endeavors and make it recognizable during conceptual design, significantly raising the design and non-design knowledge from a starting point of zero percent.

In the next chapter, the integrated product team is defined for this research. As identified in Chapter 1, there is a need in the literature to better define the members, roles, and responsibilities of an IPT before attempting to develop systems to assist them in decision making. As asserted by Verganti and supported by the literature review in Chapter 3, too often this critical step is overlooked by those espousing to develop new systems and approaches for improving conceptual design decision making.

CHAPTER V

THE CONCURRENT ENGINEERING WORKING-LEVEL INTEGRATED PRODUCT TEAM (IPT) IN THIS RESEARCH

Figure 4.1 in Chapter 4 and the GPDP IDEF0 diagrams in Chapter 2 are the high-level starting points for considering the reciprocal interdependencies that exist within the enterprise and the concept of managing them using RIM strategies. The next level of reciprocal interdependencies exist within the integrated product teams (IPTs) and the decisions they are required to make to support the activities on the IDEF0 diagrams.

Earlier in Chapter 1, the product development obstacles and concurrent engineering problems are discussed. One identified need is further definition of the types of decisions IPTs are expected to make. This need correlates with Verganti's concepts related to reciprocal interdependencies, and it supports that his research is on the right track. One of the reasons that Verganti's conclusions are so insightful with regard to improving conceptual design decision making is because it is performed within the context of teaming. Verganti's study uses real world IPTs to frame his assertions related to reciprocal interdependencies management and feedforward planning.

During the conceptual and preliminary design phases, the reciprocal interdependencies (knowledge links) between activities on the GPDP IDEF0 diagrams are being filled with the information from a relatively small number of IPT members and administrative analysts. (See Figure 4.1-Total enterprise personnel curve.) The members of an IPT support activities on the generic product development process diagram. The product designers support the Engineering activity, tool designers support the Tool Design activity, cost analysts support multiple activities, and so on. In order to improve processes, strategies, and tools used by IPTs during conceptual design, one first needs to define the members of the IPT, their primary jobs, and the types of basic decisions that they make.

A majority of the literature reviewed in Chapter 3 discusses improving the product development process and conceptual design decision making in a limited context, and very few fully recognize the complex mutual relationships that exist within an enterprise and between IPT members. As discussed in Section 4.2, the cost commitment curve in Figure 4.1 seems to *overemphasize* the technical engineering information related to cost and *underemphasize* the management of information that ultimately establishes cost. Similarly the literature seems to overemphasize the technical aspects of design information and underemphasize the management of information required to make the design a reality. Knowledge exchange between the IPT members and activities that they support that takes place after design release is often overlooked and the difficulties of managing/coordinating IPT tasks are not addressed.

In order to better understand the types of reciprocal interdependencies that exist between IPT members and how to manage them more effectively, it is necessary to define an IPT and the decisions that it is expected to make. In the next section, the responsibilities of an aircraft manufacturing working-level IPT, that is assigned the particular task of designing an NC machined bulkhead, is discussed.

5.1 Working-level IPT Responsibilities

Since the specific case for this research is aircraft manufacturing and the design of a NC machined bulkhead, it is necessary to first define some of the basic responsibilities of the working-level IPT. As stated earlier, it is very difficult to find descriptions of IPT members and responsibilities in the literature within the articles where new tools and frameworks are offered, so inferences must be made from the sources available. One source located was the "Integrated Master Plan and Schedule Guide" published by the United States Air Force Material Command (2004).

This document provides insights regarding duties IPTs are expected to carry out in support of integrated master planning (IMP) and integrated master scheduling (IMS) efforts following contract award. Some of the tasks IPTs are expected to perform, as listed in this Air Force guide are as follows:

- Identify all critical tasks for each functional discipline for all products listed as system-level events.
- Break down all IMS tasks into subtasks.
- Locate errors in the original IMS (developed during negotiations) and provide additional criteria and accomplishment information.
- Determine all technical relationships with other IPTs and coordinate them accordingly.
- Define relationships between system-level tasks, subtasks, and other IPTs with defined precedence relationships.
- Develop strategies for cross flow of information with other IPTs to avoid "team stove pipes."
- Maintain direct traceabilty between the IMS, IMP, and earned value management system (EVMS) once work commences.

- Update the IMS and IMP using EVMS information on an ongoing basis to maintain consistency once work commences.
- Generate cost estimates and cost reports for all assigned tasks and subtasks.
- Identify technology insertion candidates and associated technical requirements, cost, schedule, and risk.

The implication is that initial programmatic schedules and cost estimates are developed using a top-down approach prior to award, and that this approach does not lend itself to knowledge transfer for the purposes of managing a project. As soon as the contract is awarded, the working-level IPT is asked to perform a bottoms-up type approach to develop management information. Based on work experience, this is in fact the condition that exists.

It is very difficult to find documents published by aircraft manufacturing contractors with regard to internal performance. However, in 2001, an employee of Raytheon Systems published a report on the use of IPTs. (Rickman, 2001.) This report states that in order to get an understandable and achievable schedule and cost for their products that the IPTs had to develop, sign up for, and take personal responsibility for meeting schedule and cost targets. The IPTs were required to identify lower-level system requirements, estimate associated resource expenditures, and make the resulting information fit within the mandated confines of the contractual master schedule and budget. The implication in this report is that even though programmatic schedules and requirements estimates had already been developed, they were not in the format that IPTs could use.

Rickman's report (2001) also goes so far as to say that using IPTs at first made the concurrent engineering results worse instead of better at Raytheon because each IPT used its own approaches for determining lower-level resource requirements and schedules. In addition, the IPT difficulties described in the report deal more with the development of management information than the lack of technical engineering information availability. This lack of "management information" corresponds with the work experience of the author as well. Except for industrial engineering, few disciplines teach individuals how to correlate technical information and project management information. In addition, very few individuals have a broad enough base of experience to anticipate all of the questions IPTs have to answer. Hence, as stated in Chapter 1, there is a real need to develop systems and tools that cue IPT members regarding which decisions need to be made and provide information in a format to assist them with these decisions.

In summary, the responsibilities of the working-level IPT are quite significant. Being tasked with developing "all" of the detailed technical and management information for a project is tremendous, and in most cases, the "IPT process" is not managed or supported appropriately. In 1994, Lawson and Karandikar surveyed 70 U.S. companies, of which 35 were in the aerospace and defense sector. The significant barriers to concurrent engineering identified in this survey include: 1) poorly defined concurrent engineering processes, 2) lack of IPT training, and 3) the lack of integrating technologies.

5.2 Working-level IPT Members

In the paragraphs that follow, a discussion of generic working-level IPT members and support personnel involved in early product development decision making for an aircraft bulkhead is offered. In addition, some of the basic decisions each member is involved in are discussed.

However, keep in mind that IPTs are generally chartered to do *all* aspects of many difficult tasks, such as “determine all technical relationships with other IPTs and coordinate them accordingly.” Basically, the IPTs seem to be required to redo many tasks that has been performed previously, find the errors, figure out anything else that needs to be done, develop the plan, monitor the plan, etc. Unless an individual has actually been a member of a working-level team, it is difficult to convey that an IPT member is to become an expert at everyone else’s job, as well as convey to management what information is needed to manage.

The discussion in this chapter is not meant to imply that every aircraft manufacturing organization has the same type of membership, the descriptions are universal, or all that all possible tasks that IPTs could actually perform are listed. Instead, these representations are offered to provide more insights into the complexities that are involved in the exchange of knowledge between IPT members and how their decisions have implications to both “technical” reciprocal interdependencies and “management” reciprocal interdependencies. In addition, these discussions support the development of the RIM-based conceptual decision support system discussed later in the research.

The working-level IPT members for this research are:

- Structural design engineer (leader)
- Systems design engineer
- Test engineer
- Tool designer
- Planner

- Manufacturing engineer
- Manufacturing representative
- Purchasing representative
- Cost representatives (various; depends on program management)
- Quality assurance representative

The *structural design engineer* is typically the leader of an IPT when it involves working on a structural part, such as a bulkhead. He/she is concerned with the tasks required to complete a design that can be manufactured within specified design targets, design budget, and design release schedule. This designer works with other IPT members to make sure that the design requirements meet a variety of technical expectations and capabilities. The designer also coordinates with other designers working on the installation drawings. In addition, in order for a designer to know when the drawing must be released to meet master scheduling commitments, information related to tasks scheduled after design release must be concurrently considered.

The *systems design engineer* is concerned with the overall game plan for installing systems that will lead to penetrations in the structure, as well as sequencing issues related to structural interference. (The information needs of this IPT member are not addressed specifically in this research, so the discussion of these tasks is brief.)

The *test engineer* is concerned with testing requirements. (The information needs of this IPT member are not addressed specifically in this research, so the discussion of tasks is brief.)

The *tool designer* is responsible for conveying general feedback on tool design issues to the designer, formulating an overall tool design plan, and developing tool designs. One tool designer rarely designs all of the tools for the manufacture of a design because the tasks are too great to be accomplished within the scheduled time frame. In order for a tool designer (or management support person) to provide information to the Tool Design activity (Figure 2.6) about tooling deliverables, a projection of the release date of the engineering design is required. However, because of reciprocal interdependencies that exist between tool design tasks and the engineering design tasks, <u>the</u> release date to support the master schedule cannot be determined without establishing tooling requirements. Similarly, reciprocal interdependencies between the tool design tasks and other IPT tasks exist, and it is difficult to know when tool designs can start until the work instructions are available and in the preferred format…and so on. Many pieces of information have to be considered concurrently in order to do this job well.

The *planner* is responsible for conveying general feedback on processing issues to the designer, providing advice to the tool designer on tool manufacturing issues, developing a work instructions plan, identifying how many tool orders will have to be written, and conveying the requirements in the appropriate format to the Planning activity (Figure 2.6). One planner rarely writes all of the work instructions for tool and design manufacturing related to one design release. Instead, the work instructions are often allocated to teams of planners doing similar jobs. In order for a planner (or support person) to plan the tasks required for the Planning activity, a projected release date of the engineering drawing is required. In addition, the tool designer and the planner have to determine how many tool orders are required so that he/she can allocate resources to write them. Due to reciprocal interdependencies that exist, the planner does know when his/her tasks should start or when it should finish without considering the tasks of other IPT members concurrently.

The *manufacturing engineer* is responsible for providing additional technical information that may not be known to a planner or a tool designer. In some organizations, a manufacturing engineer actually performs some of the task described in previous paragraphs for the tool designer and planner during the early stages of design, and the contract or hourly workers do not appear on the program until later. In addition, a manufacturing engineer assists in identifying requirements for new technology insertion projects and assists with planning required manufacturing studies.

The *manufacturing representative* is responsible for representing the factory, and conveys feedback to the designer, the tool designer, the planner, and others related to perceived manufacturing preferences and requirements. This individual is also responsible for conveying to the other IPT members key information about make span requirements that will effect how manufacturing plans and organizes its tasks. This individual is also responsible for conveying to the Factory Management system information that might effect critical load dates on the master schedule, what new equipment might be needed, or other things that affect the factory's ability to perform the required manufacturing tasks. Many reciprocal interdependencies exist between the manufacturing representative and the other IPT members, and there is obvious overlap between what he/she does and some of the other technical areas. However, if the departments actually performing the work do not have a representative on teams, then this lack of participation in decision making becomes a point of contention later on.

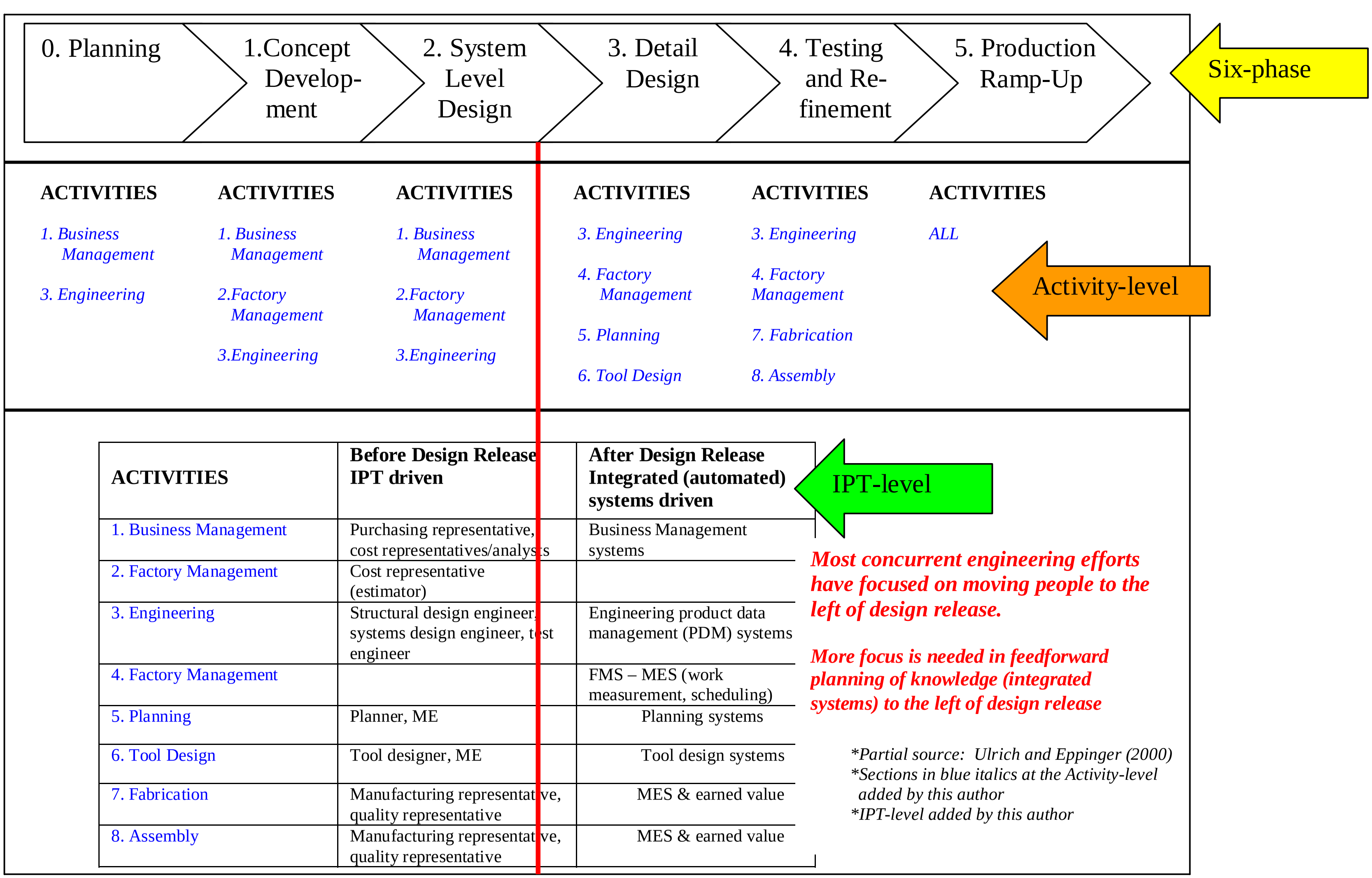
The *purchasing representative* is responsible for providing general information on vendors, as well as obtaining rough order of magnitude (ROM) and detailed quotes. To quotes from vendors, basic design requirements must be provided to the vendor. This person relays information to vendors and in return receives quotes from a vendor, which are supplied to the IPT and cost analysts. (The information needs of this IPT member are not addressed specifically in this research, so the discussion of tasks is brief.)

Various *cost representative(s)* are involved with the IPT to generate estimates or perform special studies. Depending on how the project is managed, there may be one or more persons who are involved in developing cost (and schedule) related estimates and inputting information into various systems. The Business Management activity may have an estimator assigned to pull together inputs from other estimators who report to the Engineering activity or the Factory Management activity. Or, the program may have a representative that does various types of cost estimates. The significant point is that each of these cost estimators normally has their own cost models for developing a baseline for trade studies, cost to complete exercises, and cost and schedule compression exercises. In addition, nearly all of management models/tools/reports require that the IPTs provide them with requirements, assumptions, dates, or other inputs.

The *quality assurance representative* provides input with regard to processes related to determining whether products or services meet or exceed required customer expectations. Typically these deal with program policies and objectives at a higher-level and may also deal with inspection plans. (The information needs of this IPT member are not addressed specifically in this research, so the discussion of tasks is brief.)

5.3 The Product Development Process and the Working-level IPT

At this point in the presentation it is necessary to link the generic product development process presented in Chapter 2 and the working-level IPT. Figure 5.1 is a slightly modified version of Figure 2.1. Figure 5.1 illustrates the successive levels of detail and illustrates the need for decisions support systems that support IPT efforts. In addition, Figure 5.1 illustrates that RIM and feedforward planning approaches seek to move information from right to left in the GPDP.



ACTIVITIES	Before Design Release IPT driven	After Design Release Integrated (automated) systems driven
1. Business Management	Purchasing representative, cost representatives/analysts	Business Management systems
2. Factory Management	Cost representative (estimator)	
3. Engineering	Structural design engineer, systems design engineer, test engineer	Engineering product data management (PDM) systems
4. Factory Management		FMS – MES (work measurement, scheduling)
5. Planning	Planner, ME	Planning systems
6. Tool Design	Tool designer, ME	Tool design systems
7. Fabrication	Manufacturing representative, quality representative	MES & earned value
8. Assembly	Manufacturing representative, quality representative	MES & earned value

Most concurrent engineering efforts have focused on moving people to the left of design release.

More focus is needed in feedforward planning of knowledge (integrated systems) to the left of design release

**Partial source: Ulrich and Eppinger (2000)*
**Sections in blue italics at the Activity-level added by this author*
**IPT-level added by this author*

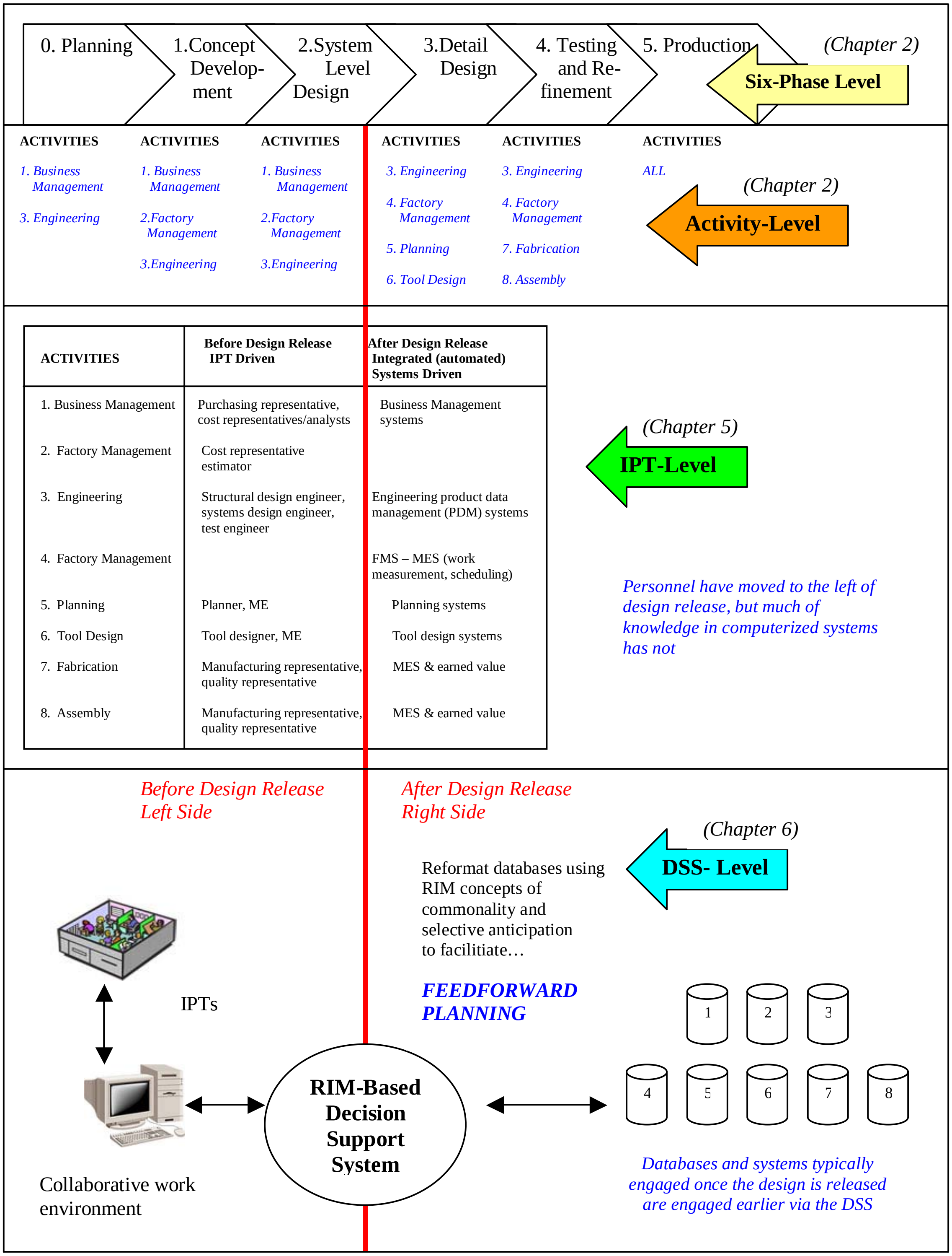
Figure 5.1 Product Development Process Six-Phase Approach With Activity-Level and IPT-Level Modifications

5.4 Summary

Teaming and the use of integrated product teams (IPTs) is the most common way in which concurrent engineering is implemented. The IPTs are usually composed of "functional" individuals who are specialists in their fields, and these individuals are a part of activities discussed in Chapter 2, as well as designated on the IDEF0 diagrams. Based on the definition of concurrent engineering, these individuals are tasked to consider "all information within the enterprise," make decisions using processes and procedures (that may not be defined), and then convey their decisions in a manner that will lead to a "management plan" resulting in the best practical quality, schedule, and cost performance. This is a tremendous undertaking, and there is no "job description" for an IPT member in the literature that reflects the overall requirements for what these individuals are being asked to do. As Verganti noted, much of the literature does not recognize the true task complexities involved in teaming decision making.

Based on earlier discussions of concurrent engineering, IPTs are required to make decisions related to: 1) technical requirements, 2) resources requirements, and 3) sequencing requirements (scheduling). Hence, in order to support IPT decision making, methodologies and tools are required that consider the reciprocal interdependencies (knowledge links) related to these types of decision making.

A generic description of a working-level IPT for the design of an aircraft bulkhead is provided. The working-level IPT decisions discussed in this chapter are used as the basis for the development of the conceptual framework of the RIM-based DSS presented in the next chapter. The RIM-based DSS presented in the next chapter add a new level to Figure 5.1 and is illustrated in Figure 5.2. Figure 5.2 is provided at this point to serve as a high-level representation of where Chapter 6 is headed.



ACTIVITIES	Before Design Release IPT Driven	After Design Release Integrated (automated) Systems Driven
1. Business Management	Purchasing representative, cost representatives/analysts	Business Management systems
2. Factory Management	Cost representative estimator	
3. Engineering	Structural design engineer, systems design engineer, test engineer	Engineering product data management (PDM) systems
4. Factory Management		FMS – MES (work measurement, scheduling)
5. Planning	Planner, ME	Planning systems
6. Tool Design	Tool designer, ME	Tool design systems
7. Fabrication	Manufacturing representative, quality representative	MES & earned value
8. Assembly	Manufacturing representative, quality representative	MES & earned value

Personnel have moved to the left of design release, but much of knowledge in computerized systems has not

Reformat databases using RIM concepts of commonality and selective anticipation to facilitate…

FEEDFORWARD PLANNING

Databases and systems typically engaged once the design is released are engaged earlier via the DSS

Figure 5.2 Product Development Process Six-Phase Approach With Activity-Level IPT-Level and DSS Level Modifications

CHAPTER VI

THE CONCEPTUAL ARCHITECTURE OF A RIM-BASED DSS AND A PROCESS FLOW DIAGRAM OF A DECISION MAKING INSTANCE

In Chapter 6, the high-level conceptual architecture of a RIM-based DSS is described and a flow diagram of a decision making instance is offered. This chapter is organized into three major subsections. The first section contains two, high-level illustrations: 1) the DSS approach in the context of Verganti's concepts (Figure 6.1) and 2) the working-level IPT decision making supported by the RIM-based DSS (Figure 6.2). The illustrations provide a view of the conceptual architecture and approach at the highest level. In the second section, conceptual information hierarchies developed using RIM concepts and RIM-diagramming are offered in groups coinciding with the activities on the IDEF0 diagrams (Chapter 2, pages 53 through 56). This section assists with making the connection between the highest level of detail in Figures 6.2 and 6.3 and the lowest level of detail offered in Chapter 7. Lastly, a flow diagram of a working-level IPT decision-making instance is overviewed to provide more insight into the reciprocal interdependencies (i.e., knowledge links) supported by the RIM-based DSS.

6.1 High-Level Representations

This section contains two, high-level illustrations:

1) Working-level IPT decision making supported by a RIM-based DSS (Figure 6.1) and
2) RIM-based decision support utilizing Verganti's concepts (Figure 6.2) and new approaches offered by this author.

These illustrations provide high-level viewpoints of the conceptual architecture and approach described in Chapter 7.

A brief discussion of terminologies found in Figures 6.1 and 6.2 is presented following the figures. The discussion is intentionally concise since Verganti's concepts and terminologies are discussed in detail in Chapter 7.

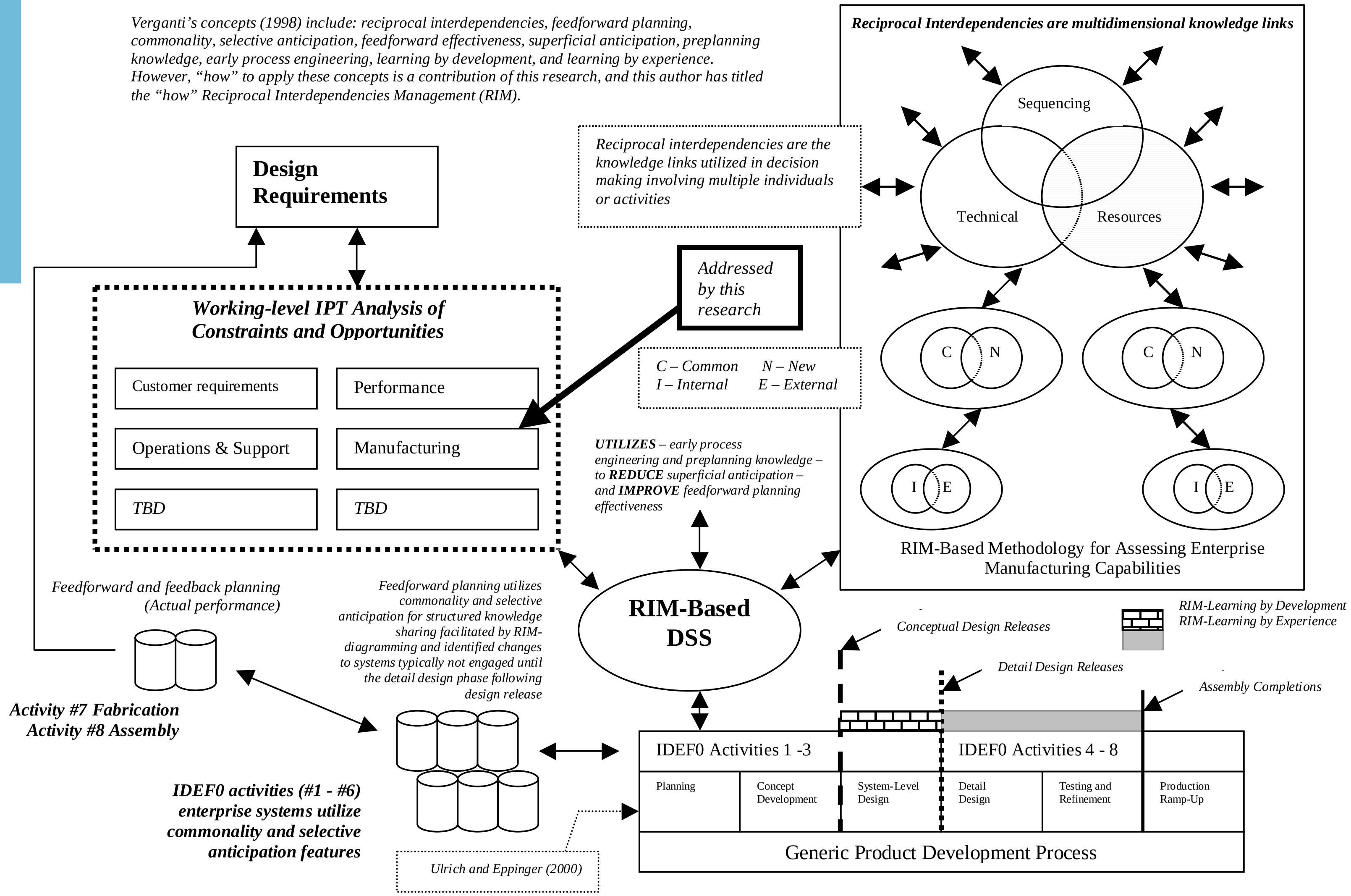
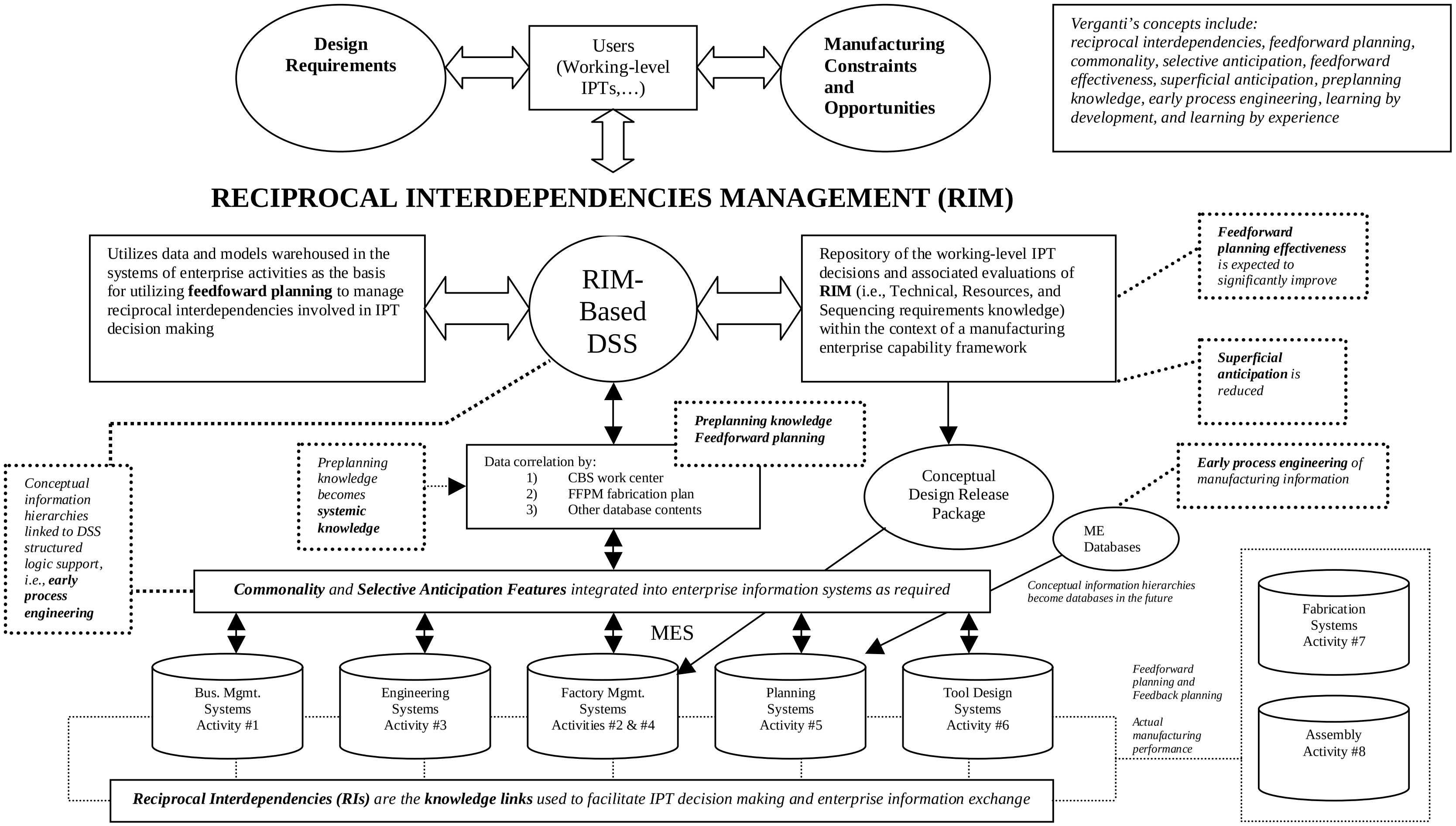


Figure 6.1 Working-Level IPT Decision Making Is Supported by a RIM-Based DSS



The conceptual hierarchies within each system support all phases of design, i.e., conceptual, preliminary, and detail. The DSS is not a stand-alone system; but instead is part of an integrated, enterprise-wide effort. The development and maintenance of data required to operate the DSS is performed by the activities. It is assumed a group within Business Management is the lead on developing the DSS and providing it as a tool for the IPTs.

Figure 6.2 RIM-Based Decision Support Approach Utilizing Verganti's High-Level Concepts and Findings

Recalling from Chapters 1 (and to be discussed further in Chapter 7), Verganti's study discusses relevant teaming survey results in the context of reciprocal interdependencies, feedforward planning, and relevant factors in order to explain key components of successful and unsuccessful concurrent engineering conceptual design efforts. Concepts, factors, and terminologies relatable to Verganti's work discussed in this research are:

- Reciprocal interdependencies management
    - Feedforward planning
    - Selective anticipation
    - Commonality
- Factors affecting and measurements of successful reciprocal interdependencies management
    - Superficial anticipation
    - Early process engineering
    - Preplanning knowledge
    - Feedforward planning effectiveness
- Types of learning potential during the product development process
    - Learning by development
    - Learning by experience

Further, even though Verganti never specifically uses the terminologies of "reciprocal interdependencies management" (RIM) or "commonality," both are implied, and thus his work is appropriately given credit. The first documented utilization of the following terminologies occurs within this research:

- Reciprocal interdependencies management (RIM)
- Design selective anticipation features
- Manufacturing selective anticipation features
- RIM-diagramming
- Commonality
- Common knowledge (in the context of RIM-diagramming)
- New knowledge (in the context of RIM-diagramming)
- RIM-learning by development
- RIM-learning by experience

In the paragraphs that follow, terminologies that appear on Figures 6.1 and 6.2 are discussed in order to facilitate understanding the descriptive details of the figures.

6.1.1 Reciprocal Interdependencies Management (RIM)

Reciprocal interdependencies management (RIM) is the collection of concepts, strategies, and methodologies used to facilitate organization and utilization of knowledge links that exist for the purposes of decision making involving multiple individuals, activities, or task groups. The concepts and strategies include, but are not limited, to feedforward planning, selective anticipation, commonality, preplanning knowledge, early process engineering, and superficial anticipation as related to the improvement of enterprise feedforward planning effectiveness.

6.1.2 Reciprocal Interdependencies

Reciprocal interdependencies (RIs) are multidimensional knowledge links between activities. They represent the information exchange that takes place between activities in order to solve a problem (or, address a question) during the product development lifecycle.

Though not specifically stated by Verganti, it can be postulated that reciprocal interdependencies occur when the accomplishment of ongoing tasks requires a mutual exchange of continuously updated/revised information between activities. In this research, reciprocal interdependencies are initially modeled for three contexts of enterprise manufacturing capability (i.e., *Technical*, *Resources*, and *Sequencing*) within subsequent categorizations of *Common*, *New*, *Internal* processes and *External* suppliers.

6.1.3 RIM-Based Methodology for Assessing Manufacturing Capability: Capability Framework

Reciprocal interdependencies are multidimensional knowledge links existing throughout an enterprise. In an attempt to bring order to the consideration of reciprocal interdependencies, an enterprise capability framework is used. First, capability is loosely defined by how well an enterprise can utilize knowledge to make decisions and achieve the desired outcomes. Second, enterprise knowledge in the context of capability is divided into three basic types of reciprocal interdependencies, i.e., technical, resources, and sequencing.

Technical reciprocal interdependencies deal with knowledge that is specialized in nature, technological, and associated with the exchange of information that is often unique to carrying out a specific task. Types of technical reciprocal interdependencies include specific knowledge related to task specific processes and tools unique to an activity.

Resources reciprocal interdependencies are knowledge links that deal with decisions related to expenditures of assets or capital within a single activity or between multiple activities. Types of reciprocal interdependencies include specific knowledge links related to labor, personnel, and procurement dollars in relation to activities. In addition, resources reciprocal interdependencies are typically used to execute the highest levels of management strategy.

Sequencing reciprocal interdependencies are knowledge links that deal the logical ordering of decisions and tasks within a single activity or between multiple activities.

Examples of sequencing reciprocal interdependencies include knowledge links related to master scheduling.

However, even the aforementioned three RIs have overlapping and soft boundaries. An example of overlap is the sequencing knowledge links used to establish the order of occurrence of technical processes or the order of occurrence of tasks within a process. Another example is assembly tolerance. Assembly tolerance sequencing has elements of both technical and sequencing reciprocal interdependencies. Similarly, the assessment of "cost" utilizes both resources and sequencing RIs, in that, cost valuation is relevant only when resources knowledge are considered in a specific window of time (sequence/order).

In summary, the capability of an enterprise is defined at a high level by how well it understands and manages the reciprocal interdependencies dealing with technical, resources, and sequencing knowledge links.

6.1.4 Commonality

Commonality is a mechanism that facilitates accomplishment of systemic learning (i.e., the capability of a company to learn from past projects and incorporate experiences). In general terms, if a system of people, facilities, and equipment is to be reused on a new project, there is a high likelihood a significant amount of "known/learned" information can be reused. The information from past experiences represents "common" knowledge. The application of commonality involves the systematic differentiation between certain aspects of a new design decision that can be satisfied by using *common knowledge* and those requiring *development of new knowledge*.

This research utilizes knowledge categories of *Common* and *New* to demonstrate the application of commonality. Further, occurrences of *Common* and *New* knowledge can be further subdivided into *internal* and *external* sources. Internal sources are in-house sources of knowledge and external sources of knowledge are related to vendors, suppliers, benchmarking, etc.

6.1.5 RIM-Diagramming

RIM-diagramming is used to strategize as to how to manage reciprocal interdependencies using previously discussed terminologies of technical, resources, sequencing, common, new, internal, and external. RIM-diagramming provides a starting point to organize knowledge in an effort to identify exchange interfaces, associated problems, and potential improvements. These diagrams help the users to focus on the premise that knowledge of new design endeavors never really begins at zero percent as suggested in many widely published figures, i.e., Chapter 4, Figure 4.1, page 103.

At first glance, a RIM-diagram looks very much like a table. However, it is being referred to as a diagram because knowledge is being segmented into parts using parallel columns. In general, RIM-diagrams have a far left column for the three basic types of reciprocal interdependencies (i.e., knowledge links) of *Technical, Resources, and Sequencing*. Next, there are columns to the right, labeled *Common* and *New*. There is no predefined number of Common and New columns. Multiple columns can be used to show how knowledge transitions during different phases of product development. In addition, there are dashed horizontal lines within the columns. The horizontal dashed line is used to further categorize the knowledge between *Internal* and *External* sources or to designate that *another type* of reciprocal interdependency is being considered simultaneously. A generic RIM-diagram is offered in Table 6.1.

Table 6.1 Generic RIM-Diagram Layout

Enterprise Manufacturing Capabilities	**Common Category 1**	**Common Category 2**	**Common Category…**	**Common Category (i)**	**New Category (j)**
Type 1:**Technical**	Internal ----------------- ***External*** Type (k) ----------------- Type (k)	Internal ----------------- ***External*** Type (k) ----------------- Type (k)	*(placeholder)*	*(placeholder)*	Internal ----------------- External ***Type (k)*** ----------------- ***Type (k)***
Type 2: **Resources**	Internal ----------------- ***External*** Type (k) ----------------- Type (k)	Internal ----------------- ***External*** Type (k) ----------------- Type (k)	*(placeholder)*	*(placeholder)*	Internal ----------------- External ***Type (k)*** ----------------- ***Type (k)***
Type 3: **Sequencing**	Internal ----------------- ***External*** Type (k) ----------------- Type (k)	Internal ----------------- ***External*** Type (k) ----------------- Type (k)	*(placeholder)*	*(placeholder)*	Internal ----------------- External ***Type (k)*** ----------------- ***Type (k)***

(i) indicates there is not a predefined number of Common columns
(j) indicates there is not a predefined number of New columns
(k) indicates there is overlap with one of the other types of reciprocal interdependencies

Arrows indicate potential knowledge links and knowledge transitional direction

Note: The elements in bold italics are not specifically addressed within this research and are marked as TBD because of the required development of supplier information.
Additionally, only very simplistic examples of ***New** Internal/External* are offered

In some RIM-diagrams, the knowledge exchange transitions downward in the diagram as *Technical* RIs are linked to *Resources* RIs and so on. Similarly, in some diagrams, the *Common* knowledge transitions are diagrammed to correlate with design stage transitions, i.e., conceptual, conceptual/preliminary, preliminary, detail, and so on. RIM-diagramming facilitates the identification of knowledge exchange issues and how to potentially alleviate problems. In most instances, the knowledge exchange issues are facilitated using conceptual information hierarchies within the conceptual DSS, which will typically become databases in an operational DSS.

In Figure 6.1, the RIM-based methodology for assessing enterprise manufacturing capability correlates to terminologies used in RIM-diagramming, i.e., Technical, Resources, Sequencing, Common, New, Internal, and External. The illustration represents the multidimensional knowledge links that exist between the eight activities on the IDEF0 diagrams in Chapter 2 at the lowest (and most complex) level of detail.

6.1.6 Feedforward Planning

Feedforward planning is a proactive approach to managing reciprocal interdependencies. The future constraints and opportunities that exist, such as in-house and supplier process capability, are anticipated and accounted for as early as possible at the level of detail required for effective decision making. Hence, if a new product should require something "totally new," this situation quickly comes to the forefront of the development process. The assumption is time spent on accounting for future constraints and opportunities is a worthwhile expenditure, in that it will more than compensate for the cost of future engineering changes.

6.1.7 Selective Anticipation

Selective anticipation is the action of determining the types of information and patterns of information use related to the verification of coherence between the product concept and future constraints, dedicating most attention to a few critical areas. In this research, the systematic documentation of selective anticipation efforts results in *design selective anticipation features* and *manufacturing anticipation features. Design selective anticipation features* are the features known with relative certainty near the beginning of the conceptual design process. Pre-identified *Manufacturing selective anticipation features* correlate to *design selective anticipation features* and convey the most desired features by process to the working-level IPT. Manufacturing selective anticipation establishes the features manufacturing would most like to have incorporated into a design. Collectively, *design selective anticipation features* and *manufacturing selective anticipation feature*s are referred to as *selective anticipation features*.

6.1.8 Superficial Anticipation

Superficial anticipation results in a baseline of assumptive information that has limited definition from which to make meaningful change or adjustment. Companies that are effective in reciprocal interdependencies management consider and manage important information earlier, and they create baseline of information useful during multiple stages of product development. Companies that perform poorly in both RIM and feedforward planning tend to confuse *superficial anticipation* with *selective anticipation*. RIM-diagramming helps to uncover multiple examples of superficial anticipation discussed in Chapter 7 with regard to how initial estimates of technical requirements, resources allocation, and associated project schedules are determined and subsequently updated. The RIM-based DSS is anticipated to potentially reduce superficial anticipation.

6.1.9 Early Process Engineering

Early process engineering entails collecting large amounts of relevant information prior to need and organizing the information in accordance to constraints and opportunities identified via selective anticipation. In particular, information related to manufacturing processes. Companies that are not effective in RIM gather large amounts of data, but do not make it useful to teaming decisions. Chapter 7 provides multiple examples of early process engineering in the context of information typically developed by manufacturing engineering but not organized appropriately for reuse. RIM-diagramming efforts highlight the need for manufacturing engineering conceptual information hierarchies, which ultimately become databases supporting the DSS.

6.1.10 Preplanning Knowledge

Preplanning knowledge is the ability to identify the tasks to be accomplished and questions to be addressed in advance of the availability of specific task information. Preplanning knowledge includes items such as checklists, contingency plans, and procedures for handling new requirements. Companies that perform better in preplanning knowledge accomplish more effectively overall RIM and feedfoward planning. The development of the RIM-based DSS itself addresses the implementation of preplanning knowledge. In addition, Chapter 7 documents how RIM-diagramming underscores the need for the development of several conceptual information hierarchies related to capacity contingency plans, the removal of information silos, and the organization of manufacturing engineering information related to new processes and equipment.

6.1.11 Feedforward Planning Effectiveness

Feedfoward planning effectiveness is the capability of a company to anticipate constraints and opportunities thereby avoiding rework and other associated problems. Feedforward effectiveness is not directly measured by overall product development project performance in terms of sales and product functionality. Just because a product sells and functions properly does not mean that the product development process utilized was an efficient one. Verganti uses a fuzzy function to measure feedforward planning effectiveness that is sensitive to the occurrences of: 1) rework, 2) engineering changes, 3) unanticipated product cost increases, and 4) missed time to market estimates. It is anticipated that the use of a RIM-based DSS facilitates improvement in overall feedforward planning effectiveness.

6.1.12 RIM-Learning by Development and RIM-Learning by Experience

RIM-learning by development relies on knowledge gained from developing a new solution, i.e., a new design. Hence, the comparison to determine *what has been learned* during development is between the conceptual design release and the final design release. Many companies do not accomplish a formal conceptual design release, and therefore, have difficulty modeling the design process. The approach suggested by this research includes the use of a formal concept design release to facilitate RIM-learning by development.

RIM-learning by experience relies on knowledge gained from actually manufacturing a past product. Hence, the comparison to determine *what has been learned* by experience is between the final configuration of the product manufactured versus the design released and the information related to the forecasted requirements of the task versus the accomplishment of the task.

6.1.13 Cost Breakdown Structure (CBS) Work Center

Cost breakdown structure (CBS) *work center* is a discretionary name used in this research to refer to the CBS designation applied to the tasks of routing jobs and accumulating labor charges by fabrication process or assembly task within the enterprise. The name used for each level of a CBS will vary by enterprise and work center is not to be confused with an industry-wide terminology. The designation of a work center is a part of an overall Business Management activity cost management strategy. The strategic use of the CBS work center structure facilitates the exchange of knowledge related to in-house processes.

6.1.14 Feedforward Planning Model (FFPM)

The feedforward planning model (FFPM) is a term used to describe the collective logic unique to the DSS. The FFPM is the mechanism facilitating the management of reciprocal interdependencies and anticipated capability at a level of detail required for effective conceptual design decision making. In many instances, the FFPM imitates/emulates the logic used by automated systems with the eight IDEF0 activities once a complete design is released.

6.1.15 Feedforward Planning Model (FFPM) Fabrication Plan

A *Feedforward Planning Model (FFPM) fabrication plan* is an assumption-based processing sequence and manufacturing plan developed and maintained by manufacturing engineering in conjunction with Fabrication activity consensus. The FFPM fabrication plan is organized by CBS work center and includes forecasted design tooling requirements by tool code by work center. The FFPM fabrication plan is initially obtained by the DSS from the Planning activity based on design selective anticipation features. The FFPM contains important information related to design complexity features, and the IPT utilizes this information as a consistent starting point for determining the most likely process sequence for the design.

Once the IPT finalizes the FFPM fabrication plan, it becomes part of the conceptual design release package and facilitates knowledge exchange between the RIM-based DSS and the manufacturing execution system (MES) within the Factory Management activity.

6.1.16 Other Database Contents

In Figure 6.2, there is a reference to “Other database contents” under the *RIM-Based DSS* circle. The conceptual information hierarchies presented within this research are envisioned to be a part of a future database scheme supporting the DSS.

6.1.17 Conceptual Design Release Package

A *conceptual design release package* is the formalization of the conceptual design requirements information in electronic format so it can be used by the manufacturing execution system. The conceptual design release package is a simulation of a detail design release package. The conceptual information hierarchies defined in Chapter 7 combined with IPT decisions made within the DSS framework support the generation of this package. Once the final design is released, the conceptual design release package offers a much-needed source of information to model the design process.

6.1.18 The Generic Product Development Process

In Chapter 2, Ulrich and Eppinger's (2000) six-phase generic product development process (i.e., planning, concept development, system level design, etc.) is further refined into eight activities on IDEF0 diagrams. Activities #1 through #8 on Figures 6.1 and 6.2 correlate to the eight activities on the IDEF0 diagrams in Chapter 2. These activities are:

1. Business Management
2. Factory Management (before design release)
3. Engineering
4. Factory Management (after design release)
5. Planning
6. Tool design
7. Fabrication
8. Assembly

6.1.19 The Segregation of Activities #7 and #8

Activities #7 and #8 (i.e., Fabrication and Assembly) are not as heavily involved in feedforward planning efforts when compared to other activities described in Chapter 7 because the knowledge related to these activities is typically maintained in the Factory Management activity. Activities #7 and #8 are more heavily oriented toward *feedback planning* and actual performance of manufacturing tasks. The manufacturing execution system (MES) within the Factory Management activity is the repository of shop floor control related knowledge.

6.1.20 Manufacturing Constraints and Opportunities

Manufacturing constraints and opportunities is a phrase utilized by Verganti. The title of the literature reference is “Anticipating Manufacturing Constraints and Opportunities in the Concept Generation and Product Planning Phases.” Thus, the term is maintained in this research for consistency.

6.1.21 Summary

The proceeding definitions and explanations provide the reader with the foundational knowledge required to correlate Figures 6.1 and 6.2 with information presented in the first five chapters of this research as well as to be presented Chapter 7.

6.2 Conceptual Architecture: A Connection of Higher-Level and Lower-Level Information

In this section, the conceptual information hierarchies presented in Chapter 7 are offered in groupings that coincide with the activities on the IDEF0 diagrams (i.e., Chapter 2, pages 53 through 56). The grouping effort is intended to assist the reader in making the connection between the highest level of detail in Figures 6.2 and 6.3 and the lowest level of detail offered in Chapter 7.

In Chapter 7, the conceptual framework for developing a RIM-based DSS is presented in the context of an aircraft manufacturing enterprise using the detailed, specific case of an NC machined bulkhead. At various points throughout Chapter 7, conceptual information hierarchies are presented. In section 6.2, the first steps toward organizing and grouping the conceptual information hierarchies to support the development of a conceptual architecture is overviewed.

Tables 6.1, 6.2, and 6.3 illustrate the beginning of the *grouping* task (i.e., organizing the individual conceptual hierarchies in accordance with the numbered activities on the IDEF0 diagrams in Chapter 2). Each table represents the collection of conceptual information hierarchies presented in Chapter 7 as being part of a *larger information system* developed and maintained by a specified activity. Table 6.1 is offered first, and an explanation of the table follows.

Table 6.2 Collections of Conceptual Information Hierarchies for the Business Management System

SYSTEM DESCRIPTION AND IDEF0 DIAGRAM ACTIVITY NUMBER	**PAGE**	**FIGURE OR TABLE REFERENCE**	**FIGURE OR TABLE DESCRIPTION**
Business Management System (IDEF0 Activity #1)			
Financial Management and Estimating			
	177	Figure 7.2	Conceptual High-Level Cost Breakdown Structure Information Hierarchies
	180	Figure 7.3	Lower-Level CBS Information Hierarchies Not Related to Detail Fabrication
	258	Figure 7.4	Lower-Level CBS Information Hierarchies for Detail Fabrication
	258	Figure 7.7	Design Processing Categories
	303	Figure 7.24	Conceptual Business Management Hierarchies
	340	Figure 7.33	Non-Recurring Engineering and Tool Design Information Hierarchies (Direct Labor and Scheduling Templates)
	297	*Figure 7.21 (Subset of Figure 7.33)*	*Non-Recurring Engineering and Tool Design Information Hierarchies (Direct Labor Templates)*
Procurement			
	303	Figure 7.22	Make/Buy Policies Management Conceptual Information Hierarchies
	340	Figure 7.34	
	299	*Figure 7.23 (Subset of Figure 7.34)*	*Procurement Management Conceptual*

The first column of Tables 6.1 through 6.3 contains the description of the system and the IDEF0 activity number with which it is associated. (IDEF0 diagrams previously presented in Chapter 2, pages 53 through 56.)

The second column provides a page reference where the conceptual information hierarchy is presented. (Note pages 258, 303, 316, and 340 are pages where multiple conceptual information hierarchies are collected within a major section of Chapter 7.)

The third column lists the figure number or table number reference. In some instances, the reference is italicized. The italics indicate the reference is a subset of the prior reference. For example, in Table 6.1, Figure 7.21 is italicized. The conceptual information hierarchy in Figure 7.21 was developed first in Chapter 7, and subsequently the information hierarchy was updated to Figure 7.34. Hence, Figure 7.21 is a subset of Figure 7.34. The fourth columns of Tables 6.1 through 6.3 contain the descriptions for each figure or table reference in the third column.

Figure 6.3 provides an illustration of the conceptual hierarchies grouped in accordance to Table 6.1. Figure 6.3 is not intended to represent linkages of order; but is only offered to assist the reader with recalling the conceptual information hierarchies presented in Chapter 7.

- Aircraft System Cost
  - Engineering
    - Design (Nonrecurring) [designer]
    - Recurring
  - Tooling
    - Nonrecurring (1st article & rate tooling)
      - Tool design
        - Tool design [tool designer]
        - Work instructions [planner]
        - Tool engineering [manufacturing engineer]
      - Tool manufacturing
        - Tooling material
        - Tooling labor
    - Recurring (sustaining tool maintenance)
  - Quality
    - Nonrecurring quality assurance
    - Recurring inspection and test
  - Recurring Production
    - Manufacturing
      - Manufacturing material
        - Material direct
        - Material indirect [purchasing representative]
      - Manufacturing overhead
        - Manufacturing indirect [industrial engineer]
      - Manufacturing labor
        - Manufacturing direct [touch labor]
        - Manufacturing indirect [manufacturing supervision and direct support; manufacturing representatives]
  - Project Management
    - Other [other cost engineers]
  - TBD
  - TBD

Figure 7.2 Conceptual High-Level Cost Breakdown Structure Information Hierarchies

- Final Assembly
  - Mate & Complete
  - Paint
- Component Assembly
  - (multiple levels for structure and systems)
- Mechanical Subassembly
  - (multiple levels)
- Special Fabrication and Subassembly
  - Welding
    - Electron Beam
    - Laser Beam
  - Electrical Components (Electrical)
    - Harnesses
    - Cables
  - Tubing and Ducts (Plumbing)
    - Tubing & duct fabrication
    - Tubing & duct assembly
  - Other….

Figure 7.3 Lower-Level CBS Information Hierarchies Not Related to Detail Fabrication

- Project /Program
  - WBS
  - SWBS (Master Schedule)
  - CBS
  - Accounting months
  - Factors
    - Non recurring
      - TBD
      - TBD
    - Recurring
      - TBD
      - TBD
  - Rates
    - Non recurring
      - TBD
      - TBD
    - Recurring
      - TBD
      - TBD
  - Learning curves
    - Assembly CBS number
      - TBD
      - TBD
    - Fabrication CBS number
      - TBD
      - TBD
    - Other
      - TBD

Figure 7.24 Conceptual Business Management Information Hierarchies

- Detail Fabrication
  - Composites Fabrication
    - TBD (hierarchies not defined or discussed)
  - Sheet Metal Fabrication
    - TBD (hierarchies not defined or discussed)
  - NC Milling and Support **[Group 1 of 9]**
    - NC Milling
      - 3-Axis milling *(work center level)*
      - 5-Axis milling
      - 5-Axis high speed milling
    - Specialty Hole Processing (Equipment) **[Group 2 of 9]**
      - Drilling/Boring type 1 *(work center level)*
      - Drilling/Boring type 2
      - 3-Axis (tooling holes)
    - Minor Subassembly for NC Machined Parts [Not discussed]
      - Hole processing *(work center level)*
      - Bushing installation
      - Nutplate installation
    - Hand Finish **[Group 3 of 9]**
      - Vapor degrease *(work center level)*
      - Deburr
      - Hole processing (portable systems)
      - Tooling tab removal
  - Coatings **[Group 4 of 9]**
    - Wash/Clean *(work center level)*
    - Mask
    - Prime
    - Paint
    - Electrical bonding
    - Seal bonding (not discussed)
  - Hardening and/or Special Treatment **[Group 5 of 9]**
    - Wash/Clean *(work center level)*
    - Heat treat
    - Heat treat age
  - Chemical Processing **[Group 6 of 9]**
    - Wash/Clean *(work center level)*
    - Chemical milling
    - Annodize
    - Plating
  - Forming [**Group 7 of 9]**
    - Wash/Clean *(work center level)*
    - Shot peen
  - Marking [**Group 8 of 9]**
    - Stamping *(work center level)*
    - Vibroengrave
- Detail Fabrication Quality Assurance [**Group 9 of 9]**
  - Plate inspection
  - Intermediate inspection
  - Non-destructive testing
  - Final inspection
  - TBD

Figure 7.4 Lower-Level CBS Information Hierarchies for Detail Fabrication

- Design Processing Categories
  - Shaping
    - Forging + Machining
    - NC Machining
    - Sheet Metal Fabrication
    - Composites
    - Other (TBD)
  - Mechanical Assembly
  - Electrical Harnesses and Cables (Electrical)
  - Tubing and Ducts (Plumbing)
  - TBD

Figure 7.7 Information Hierarchies for Design Processing Categories

- Project
  - Design selective anticipation features
    - Detail design templates
      - Design hours
      - *Design M-days*
      - Work instructions hours
      - *Work instructions M-days*
    - Tool code templates
      - Tool model hours
      - *Tool model M-days*
      - Tool design hours
      - *Tool design M-days*
      - Tool manufacturing work instructions hours
      - *Tool manufacturing work instructions M-days*

Figure 7.33 Non-Recurring Engineering and Tool Design Direct Labor and Scheduling Conceptual Information Hierarchies (Updated Figure 7.23)

- Make/Buy Policies
  - Processing categories
    - NC machining (make)
    - Processing category x (make, buy)
    - Processing category (make, buy)
    - TBD
  - Design type
    - Bulkhead xxx NC machining (buy)
    - TBD
  - Design Tools
    - Tool code y
      - Control number xxx (make)
    - Tool code z
      - Control number xxx (buy)
    - TBD
- Raw Materials
  - Material a
  - Material b
  - TBD

Figure 6.22 Make/Buy Policies Management Conceptual Information Hierarchies

- Raw Material
  - M&P material code
    - Plate
      - Standard sizes
        - Vendors
          - Cost (BY, unburdened $)
          - Order history (M-days)
          - *Order history (M-days)*
        - Project templates
          - Project x
          - Cost (BY, unburdened $)
          - *Order history (M-days)*
    - Bar stock
      - Same as plate
        - “”
    - TBD
      - Same as plate
        - “”
    - Tool Code
      - Where used
        - Design selective anticipation features
          - Standardized ranges
            - Vendors (historical data)
              - Cost (BY, unburdened $)
              - *Order history (M-days)*
            - Project templates
              - Project x
              - Cost (BY, unburdened $)
              - *Order history (M-days)*
  - ROM Quotes
    - Design number
    - Tool number
    - TBD
  - Final Bids
    - Design number
    - Tool number
    - TBD
  - TBD

Figure 7.34 Procurement Management Conceptual Information Hierarchies (Update of Figure 7.23 Reflecting Scheduling Templates

Business Management Activity #1

Figure 6.3 Business Management System: Conceptual Information Hierarchies Supporting the DSS

On the next four pages, Tables 6.2 and 6.3 and Figures 6.4 and 6.5 are offered to illustrate the remainder of the *grouping* task associated with conceptual hierarchies presented in Chapter 7.

Table 6.3 Collections of Conceptual Information Hierarchies for the Factory Management and Engineering Product Data Management Systems

SYSTEM DESCRIPTION AND IDEF0 DIAGRAM ACTIVITY NUMBER	**PAGE**	**FIGURE OR TABLE REFERENCE**	**FIGURE OR TABLE DESCRIPTION**
Factory Management System (IDEF0 Activities #2 and #4)			
	303	Figure 7.19	Information Silos Converted Into Conceptual Information Hierarchies
	197	*Figure 7.5 (Subset of Figure 7.19)*	*CBS Work Center (WC) Data*
	303	Figure 7.20	Work Measurement System Conceptual Information Hierarchies
	316	Figure 7.27	Capacity Conceptual Information Hierarchies
	316	Figure 7.28	Scheduling Conceptual Information Hierarchies
	340	Figure 7.32	Conceptual Information Hierarchies to Support MES Simulation of CBS Work Center Internal Schedule Makespan (Setback)
Engineering Product Data Management System (IDEF0 Activity #3)			
	258	Figure 7.10	PDMS Conceptual Information Hierarchies
	207	*Figure 7.8 (Subset of 7.10)*	*Design Selective Anticipation Features*
	175	*Figure 7.1 (Subset of 7.10)*	*Product Structure*

- CBS Work Center (WC) Data
  - WC number
  - WC location
  - WC layout
  - Process descriptions
  - Worker classifications
  - *Material handling information*
    - *WC ingress/egress correlated to features*
  - Processing system information
    - Most used M & P Specs
    - Non-design tools
    - Equipment inventory
      - Correlated to features (TBD)

Figure 7.19 Information Silos Transformed Into
Conceptual Information Hierarchies
(Updated From Figure 7.5)

- Work Measurement
  - Work center number
    - Process studies
    - Material handling constraints based on design selective anticipation features
    - Grouped standard CERs sensitive to design selective anticipation features
    - Detail features-based standard values (sensitive to all features; for specific application to nearly complete design)
    - TBD

Figure 7.20 WMS Conceptual Information
Hierarchies

- Capacity
  - Work center number
    - Max headcount by shift
    - Max machines by shift
    - Max actual hours available by shift by accounting month
    - Forecast actual hours firm planned (complete designs) by shift by accounting month
      - Firm planned Capacity (complete designs) by shift by accounting month
      - Available capacity remaining by shift by accounting month
      - Contingency plans
      - TBD
- CRP Simulation
  - Work center
    - Realization factor
      - Other factors
      - TBD

Figure 7.27 Capacity Conceptual
Information Hierarchies

- Scheduling
  - SWBS
    - Work center number
      - M-days
  - Historical data
    - Work center makespan (setback)
      - Design selective anticipation features
      - Tool design selective anticipation features (not defined in this research)
      - TBD

Figure 7.28 Scheduling Conceptual
Information Hierarchies

- MES Simulation
  - CBS Work center
    - Design selective anticipation features
      - Schedule makespan (M-days)

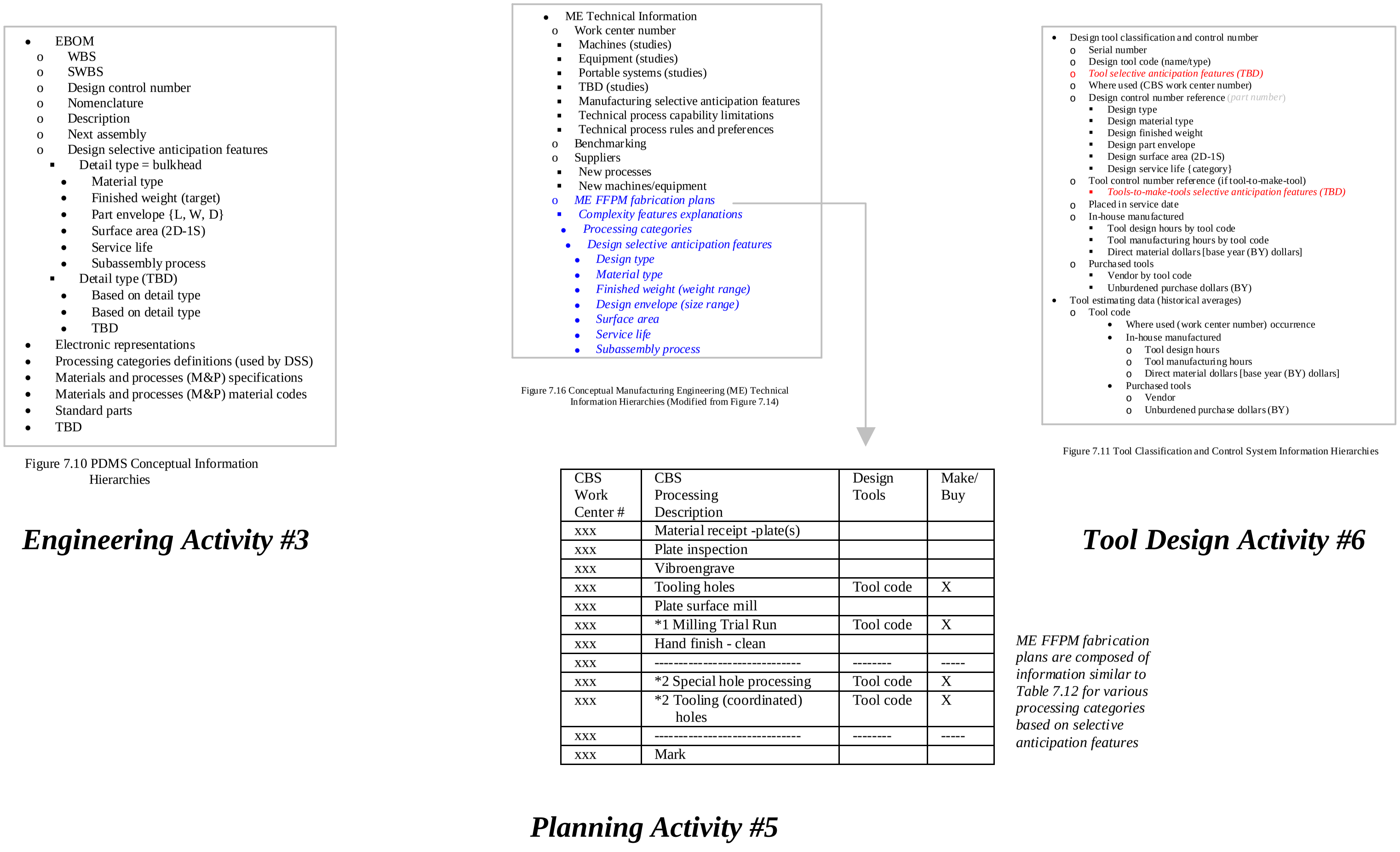
Figure 7.32 Conceptual Information Hierarchies
to Support MES Simulation of CBS
Work Center Internal Schedule Makespan
(or Setback)

Factory Management #2 (Pre-Design Release) and #4 (Post-Design Release)

Figure 6.4 Factory Management System: Conceptual Information Hierarchies Supporting the DSS

Table 6.4 Collections of Conceptual Information Hierarchies for the Planning System and the Tool Design and Control System

SYSTEM DESCRIPTION AND IDEF0 DIAGRAM ACTIVITY NUMBER	**PAGE**	**FIGURE OR TABLE REFERENCE**	**FIGURE OR TABLE DESCRIPTION**
Planning System (IDEF0 Activity #5)			
	258	Figure 7.16	Conceptual Manufacturing Engineering (ME) Technical Information Hierarchies (Update of Figure 6.14)
	237	*Figure 7.14* *(Subset of Figure 7.16)*	Conceptual Manufacturing Engineering (ME) Technical Information Hierarchies
	249	*Table 7.12* *(Subset of Figure 7.16)*	Conceptual FFPM Fabrication Plan (Processing Sequence)
Tool Design and Control System (IDEF0 Activity #6)			
	258	Figure 7.11	Tool Classification and Control System Information Hierarchies



- EBOM
  - WBS
  - SWBS
  - Design control number
  - Nomenclature
  - Description
  - Next assembly
  - Design selective anticipation features
    - Detail type = bulkhead
      - Material type
      - Finished weight (target)
      - Part envelope {L, W, D}
      - Surface area (2D-1S)
      - Service life
      - Subassembly process
    - Detail type (TBD)
      - Based on detail type
      - Based on detail type
      - TBD
- Electronic representations
- Processing categories definitions (used by DSS)
- Materials and processes (M&P) specifications
- Materials and processes (M&P) material codes
- Standard parts
- TBD

Figure 7.10 PDMS Conceptual Information Hierarchies

Engineering Activity #3

- ME Technical Information
  - Work center number
    - Machines (studies)
    - Equipment (studies)
    - Portable systems (studies)
    - TBD (studies)
    - Manufacturing selective anticipation features
    - Technical process capability limitations
    - Technical process rules and preferences
  - Benchmarking
  - Suppliers
    - New processes
    - New machines/equipment
  - *ME FFPM fabrication plans*
    - *Complexity features explanations*
    - *Processing categories*
    - *Design selective anticipation features*
      - *Design type*
      - *Material type*
      - *Finished weight (weight range)*
      - *Design envelope (size range)*
      - *Surface area*
      - *Service life*
      - *Subassembly process*

Figure 7.16 Conceptual Manufacturing Engineering (ME) Technical Information Hierarchies (Modified from Figure 7.14)

CBS Work Center #	CBS Processing Description	Design Tools	Make/ Buy
xxx	Material receipt -plate(s)		
xxx	Plate inspection		
xxx	Vibroengrave		
xxx	Tooling holes	Tool code	X
xxx	Plate surface mill		
xxx	*1 Milling Trial Run	Tool code	X
xxx	Hand finish - clean		
xxx	------------------------------	--------	-----
xxx	*2 Special hole processing	Tool code	X
xxx	*2 Tooling (coordinated) holes	Tool code	X
xxx	------------------------------	--------	-----
xxx	Mark		

Planning Activity #5

- Design tool classification and control number
  - Serial number
  - Design tool code (name/type)
  - *Tool selective anticipation features (TBD)*
  - Where used (CBS work center number)
  - Design control number reference *(part number)*
    - Design type
    - Design material type
    - Design finished weight
    - Design part envelope
    - Design surface area (2D-1S)
    - Design service life {category}
  - Tool control number reference (if tool-to-make-tool)
    - *Tools-to-make-tools selective anticipation features (TBD)*
  - Placed in service date
  - In-house manufactured
    - Tool design hours by tool code
    - Tool manufacturing hours by tool code
    - Direct material dollars [base year (BY) dollars]
  - Purchased tools
    - Vendor by tool code
    - Unburdened purchase dollars (BY)
- Tool estimating data (historical averages)
  - Tool code
    - Where used (work center number) occurrence
    - In-house manufactured
      - Tool design hours
      - Tool manufacturing hours
      - Direct material dollars [base year (BY) dollars]
    - Purchased tools
      - Vendor
      - Unburdened purchase dollars (BY)

Figure 7.11 Tool Classification and Control System Information Hierarchies

Tool Design Activity #6

ME FFPM fabrication plans are composed of information similar to Table 7.12 for various processing categories based on selective anticipation features

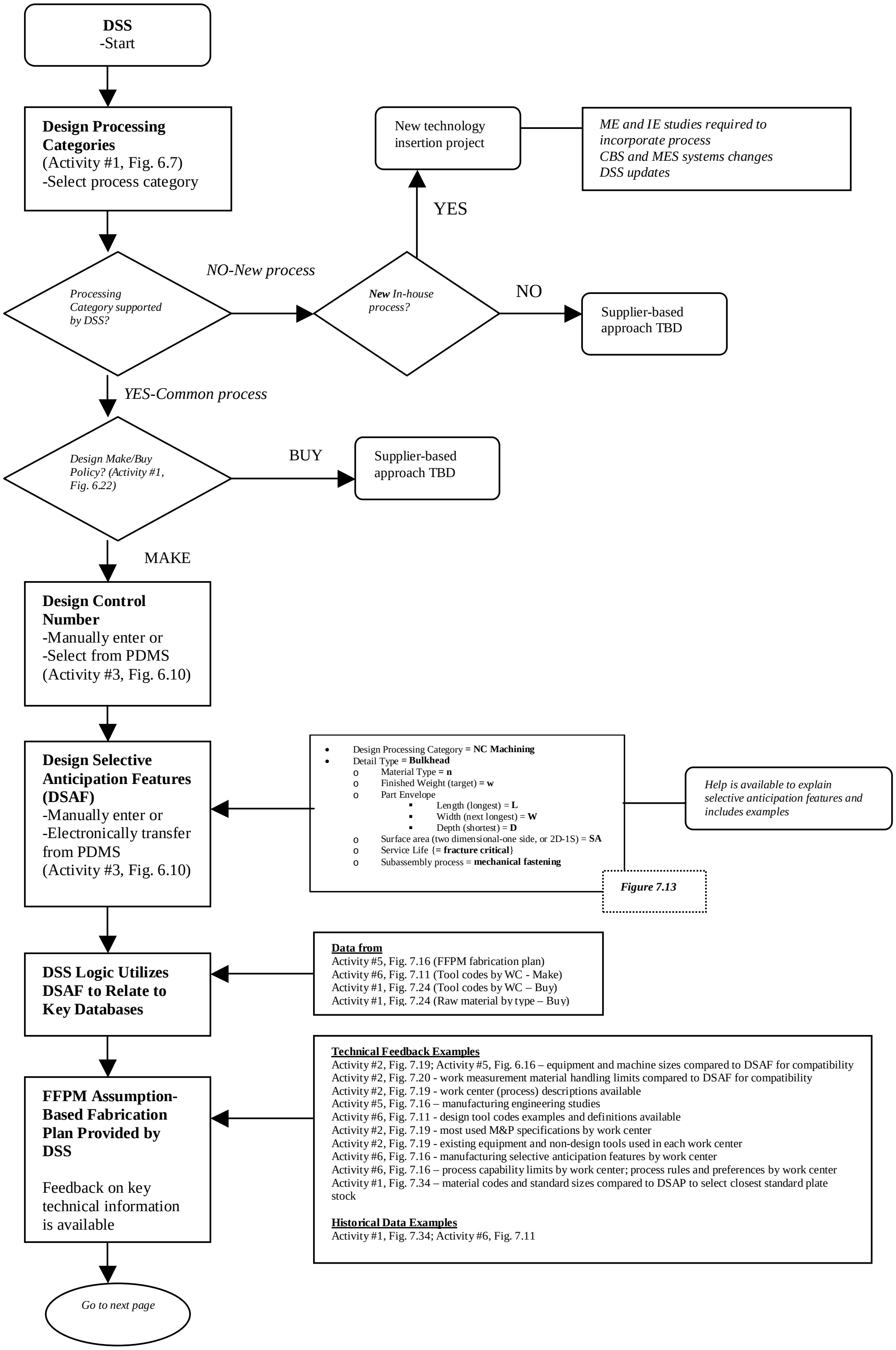
Figure 6.5 Engineering, Planning, and Tooling Systems: Conceptual Information Hierarchies Supporting the DSS

Section 6.3 A Flow Diagram of a Decision Making Instance

This section provides a flow diagram of a working-level IPT decision-making instance illustrates to provide the reciprocal interdependencies (i.e., knowledge links) and information exchange supported by the RIM-based DSS. The flow diagram is composed of a series of 11 figures, Figures 6.6 through 6.16.

Recall the figures are referring to conceptual information hierarchies from Chapter 7 are summarized in Figures 6.3 through 6.5. These three figures provide a useful reference when reviewing the flow diagram figures.

These flow diagram figures describe the envisioned operation of the DSS at a very high level. They also provide a means to further assimilate the conceptual information hierarchies from Chapter 7.



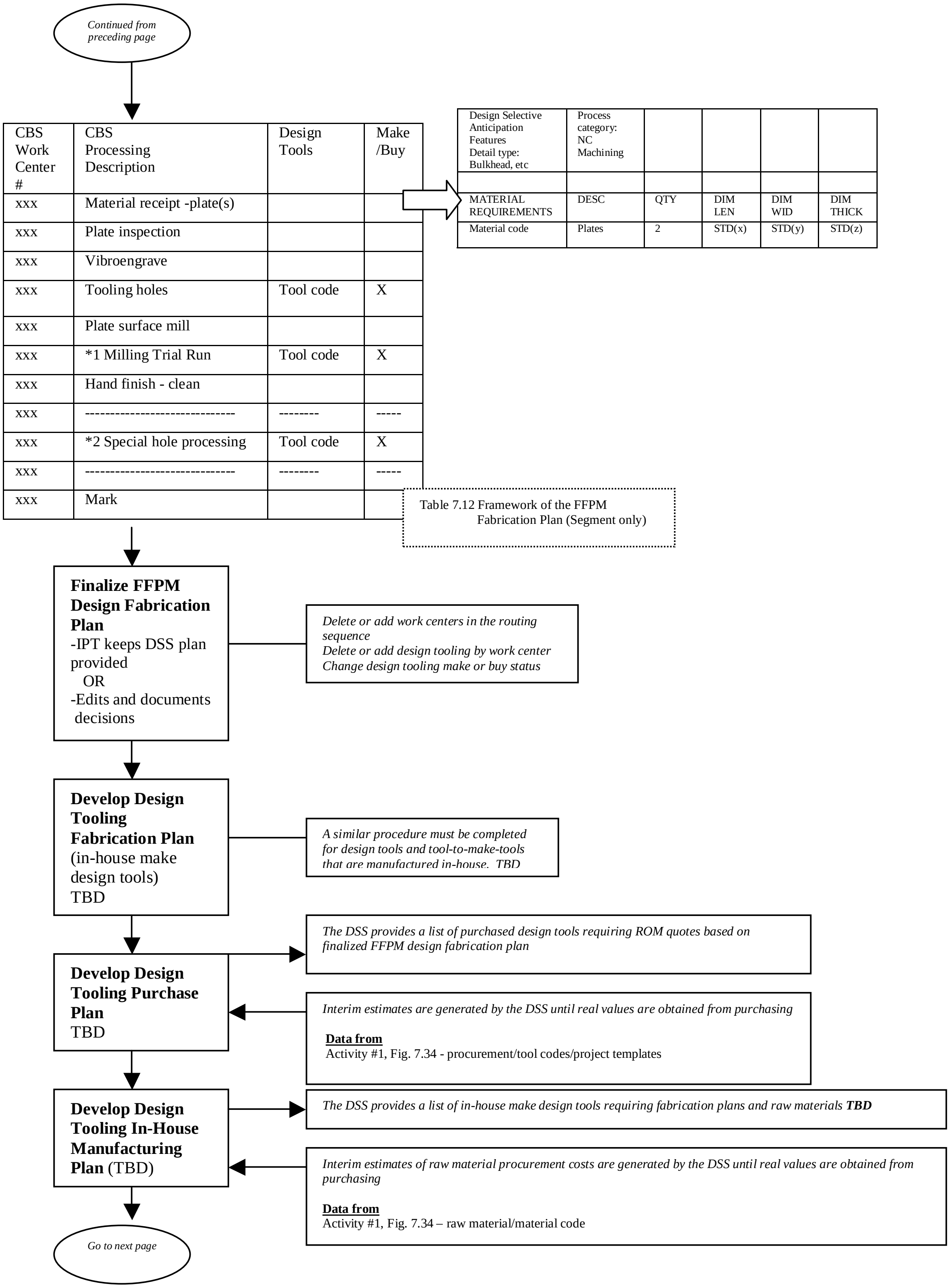
- Design Processing Category = **NC Machining**
- Detail Type = **Bulkhead**
    - Material Type = **n**
    - Finished Weight (target) = **w**
    - Part Envelope
        - Length (longest) = **L**
        - Width (next longest) = **W**
        - Depth (shortest) = **D**
    - Surface area (two dimensional-one side, or 2D-1S) = **SA**
    - Service Life {= **fracture critical**}
    - Subassembly process = **mechanical fastening**

Data from
Activity #5, Fig. 7.16 (FFPM fabrication plan)
Activity #6, Fig. 7.11 (Tool codes by WC - Make)
Activity #1, Fig. 7.24 (Tool codes by WC – Buy)
Activity #1, Fig. 7.24 (Raw material by type – Buy)

Technical Feedback Examples
Activity #2, Fig. 7.19; Activity #5, Fig. 6.16 – equipment and machine sizes compared to DSAF for compatibility
Activity #2, Fig. 7.20 - work measurement material handling limits compared to DSAF for compatibility
Activity #2, Fig. 7.19 - work center (process) descriptions available
Activity #5, Fig. 7.16 – manufacturing engineering studies
Activity #6, Fig. 7.11 - design tool codes examples and definitions available
Activity #2, Fig. 7.19 - most used M&P specifications by work center
Activity #2, Fig. 7.19 - existing equipment and non-design tools used in each work center
Activity #6, Fig. 7.16 - manufacturing selective anticipation features by work center
Activity #6, Fig. 7.16 – process capability limits by work center; process rules and preferences by work center
Activity #1, Fig. 7.34 – material codes and standard sizes compared to DSAP to select closest standard plate stock

Historical Data Examples
Activity #1, Fig. 7.34; Activity #6, Fig. 7.11

Figure 6.6 Flow Diagram of DSS Operation: 1 of 11

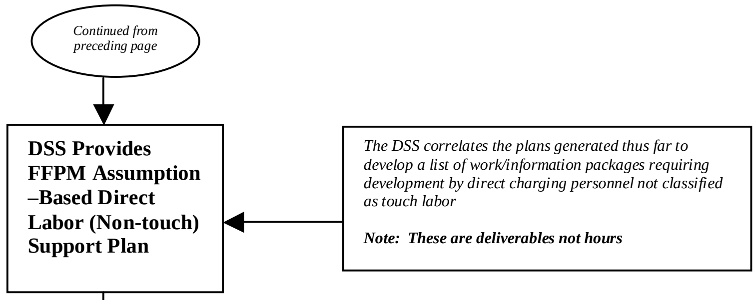


CBS Work Center #	CBS Processing Description	Design Tools	Make /Buy
xxx	Material receipt -plate(s)		
xxx	Plate inspection		
xxx	Vibroengrave		
xxx	Tooling holes	Tool code	X
xxx	Plate surface mill		
xxx	*1 Milling Trial Run	Tool code	X
xxx	Hand finish - clean		
xxx	------------------------------	--------	-----
xxx	*2 Special hole processing	Tool code	X
xxx	------------------------------	--------	-----
xxx	Mark		

Design Selective Anticipation Features Detail type: Bulkhead, etc	Process category: NC Machining				
MATERIAL REQUIREMENTS	DESC	QTY	DIM LEN	DIM WID	DIM THICK
Material code	Plates	2	STD(x)	STD(y)	STD(z)

Table 7.12 Framework of the FFPM Fabrication Plan (Segment only)

Figure 6.7 Flow Diagram of DSS Operation: 2 of 11



Related Work or Information Packages	Qty	Direct Charging Activity	Override Notes
Requirements List			
Detail designs	1		As required
Design tools (make)	X		As required
Design tools (buy)	Y		As required
Deliverables List			
Detail designs	1	Engineering activity	As required
Design fabrication tool orders	X+Y	Planning activity	As required
Design fabrication work instructions	1	Planning activity	
Tool fabrication work instructions	X	Planning activity	As required
Tool models	X+Y	Tool design activity	As required
Tool designs	X	Tool design activity	As required

DSS logic discussed in Section 7.12

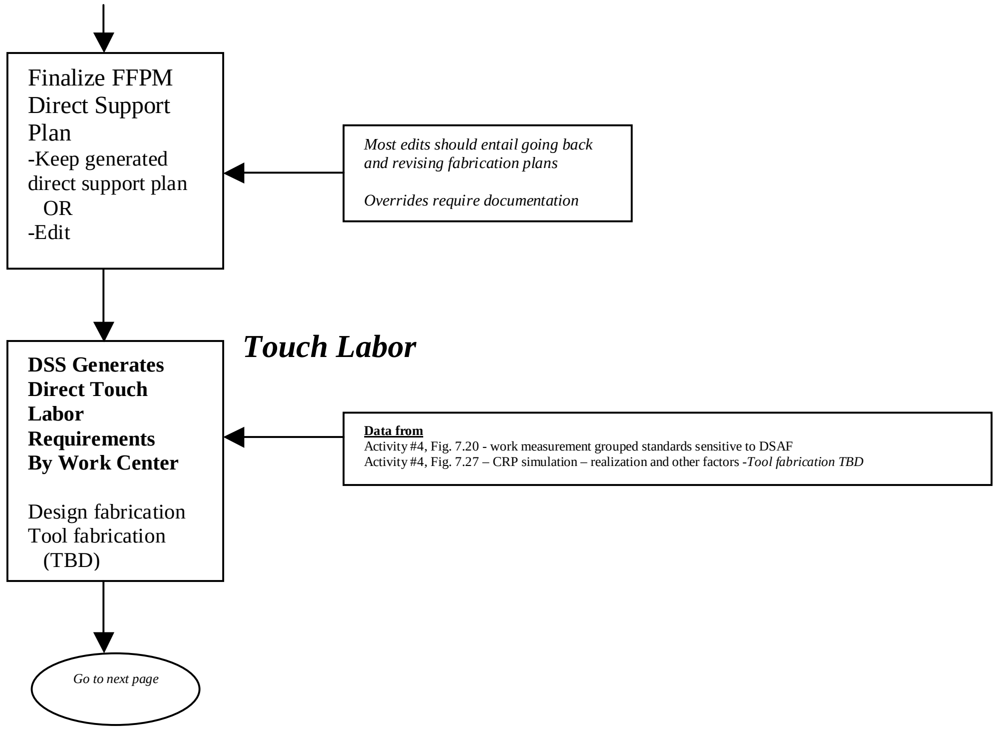
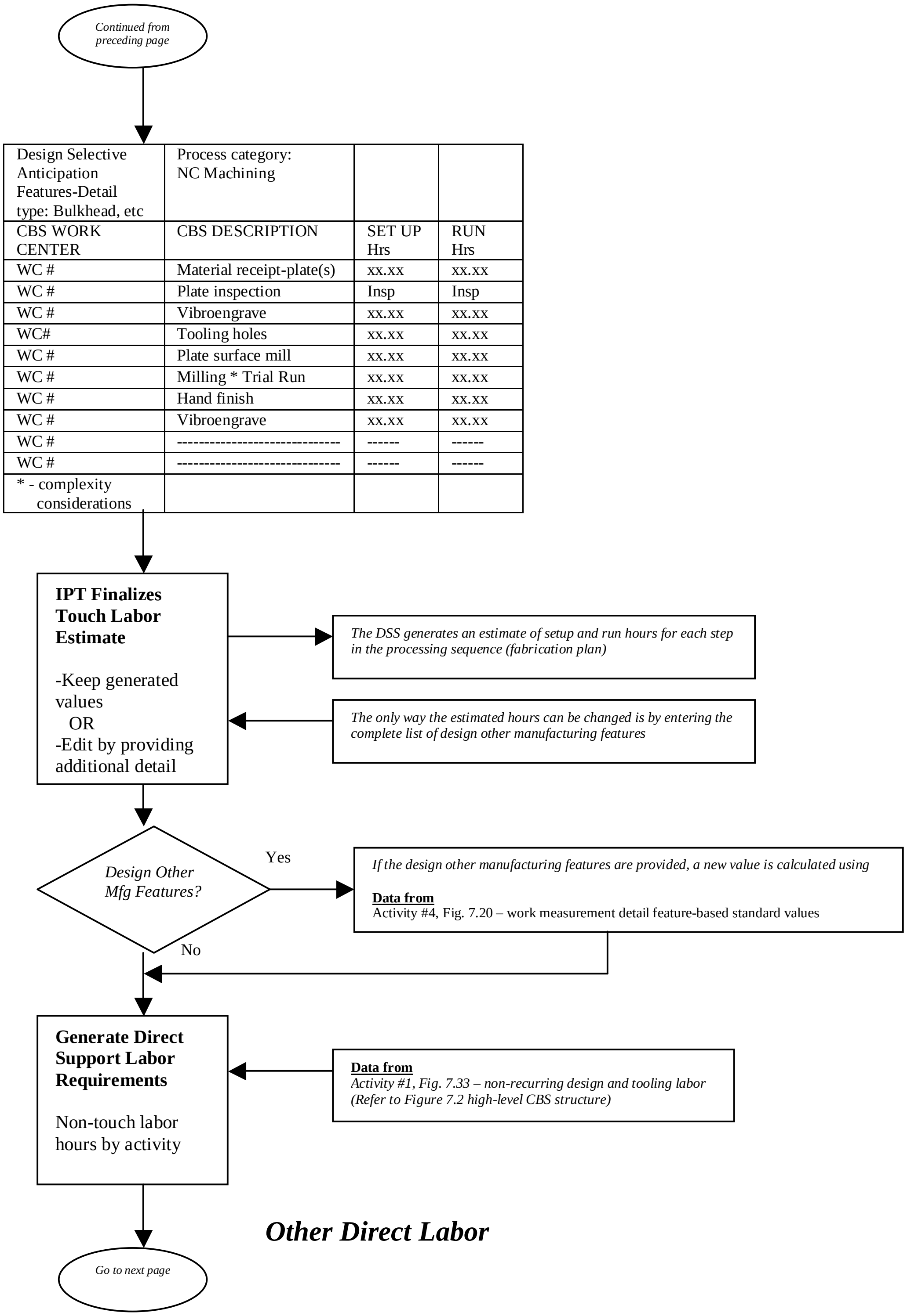


Figure 6.8 Flow Diagram of DSS Operation: 3 of 11



Design Selective Anticipation Features-Detail type: Bulkhead, etc	Process category: NC Machining		
CBS WORK CENTER	CBS DESCRIPTION	SET UP Hrs	RUN Hrs
WC #	Material receipt-plate(s)	xx.xx	xx.xx
WC #	Plate inspection	Insp	Insp
WC #	Vibroengrave	xx.xx	xx.xx
WC#	Tooling holes	xx.xx	xx.xx
WC #	Plate surface mill	xx.xx	xx.xx
WC #	Milling * Trial Run	xx.xx	xx.xx
WC #	Hand finish	xx.xx	xx.xx
WC #	Vibroengrave	xx.xx	xx.xx
WC #	------------------------------	------	------
WC #	------------------------------	------	------
* - complexity considerations			

IPT Finalizes Touch Labor Estimate

-Keep generated values
OR
-Edit by providing additional detail

The DSS generates an estimate of setup and run hours for each step in the processing sequence (fabrication plan)

The only way the estimated hours can be changed is by entering the complete list of design other manufacturing features

Design Other Mfg Features?

If the design other manufacturing features are provided, a new value is calculated using

Data from
Activity #4, Fig. 7.20 – work measurement detail feature-based standard values

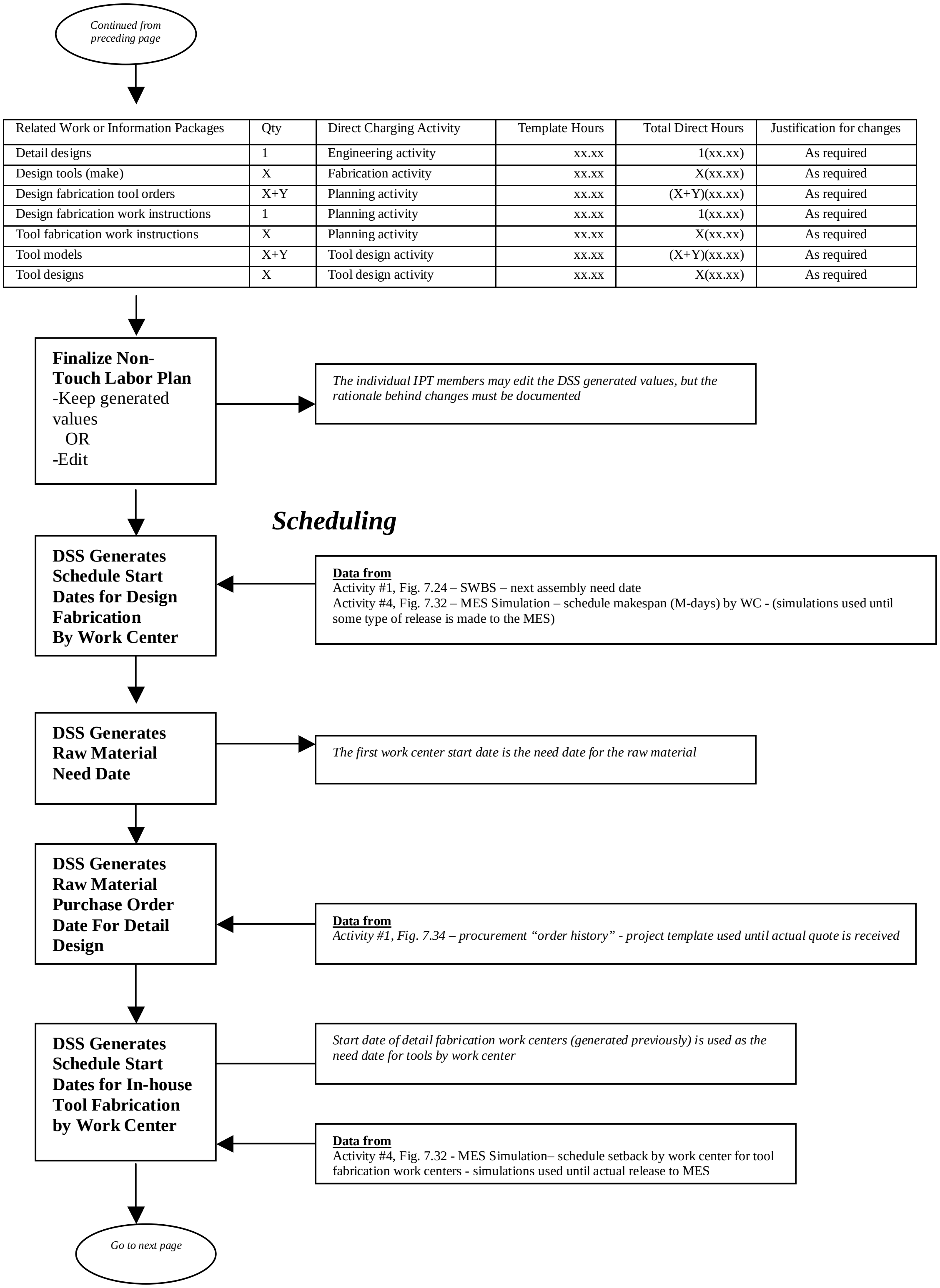
Generate Direct Support Labor Requirements

Non-touch labor hours by activity

Data from
Activity #1, Fig. 7.33 – non-recurring design and tooling labor (Refer to Figure 7.2 high-level CBS structure)

Other Direct Labor

Figure 6.9 Flow Diagram of DSS Operation: 4 of 11



Related Work or Information Packages	Qty	Direct Charging Activity	Template Hours	Total Direct Hours	Justification for changes
Detail designs	1	Engineering activity	xx.xx	1(xx.xx)	As required
Design tools (make)	X	Fabrication activity	xx.xx	X(xx.xx)	As required
Design fabrication tool orders	X+Y	Planning activity	xx.xx	(X+Y)(xx.xx)	As required
Design fabrication work instructions	1	Planning activity	xx.xx	1(xx.xx)	As required
Tool fabrication work instructions	X	Planning activity	xx.xx	X(xx.xx)	As required
Tool models	X+Y	Tool design activity	xx.xx	(X+Y)(xx.xx)	As required
Tool designs	X	Tool design activity	xx.xx	X(xx.xx)	As required

Finalize Non-Touch Labor Plan
-Keep generated values
OR
-Edit

The individual IPT members may edit the DSS generated values, but the rationale behind changes must be documented

Scheduling

DSS Generates Schedule Start Dates for Design Fabrication By Work Center

Data from
Activity #1, Fig. 7.24 – SWBS – next assembly need date
Activity #4, Fig. 7.32 – MES Simulation – schedule makespan (M-days) by WC - (simulations used until some type of release is made to the MES)

DSS Generates Raw Material Need Date

The first work center start date is the need date for the raw material

DSS Generates Raw Material Purchase Order Date For Detail Design

Data from
Activity #1, Fig. 7.34 – procurement "order history" - project template used until actual quote is received

DSS Generates Schedule Start Dates for In-house Tool Fabrication by Work Center

Start date of detail fabrication work centers (generated previously) is used as the need date for tools by work center

Data from
Activity #4, Fig. 7.32 - MES Simulation– schedule setback by work center for tool fabrication work centers - simulations used until actual release to MES

Figure 6.10 Flow Diagram of DSS Operation: 5 of 11

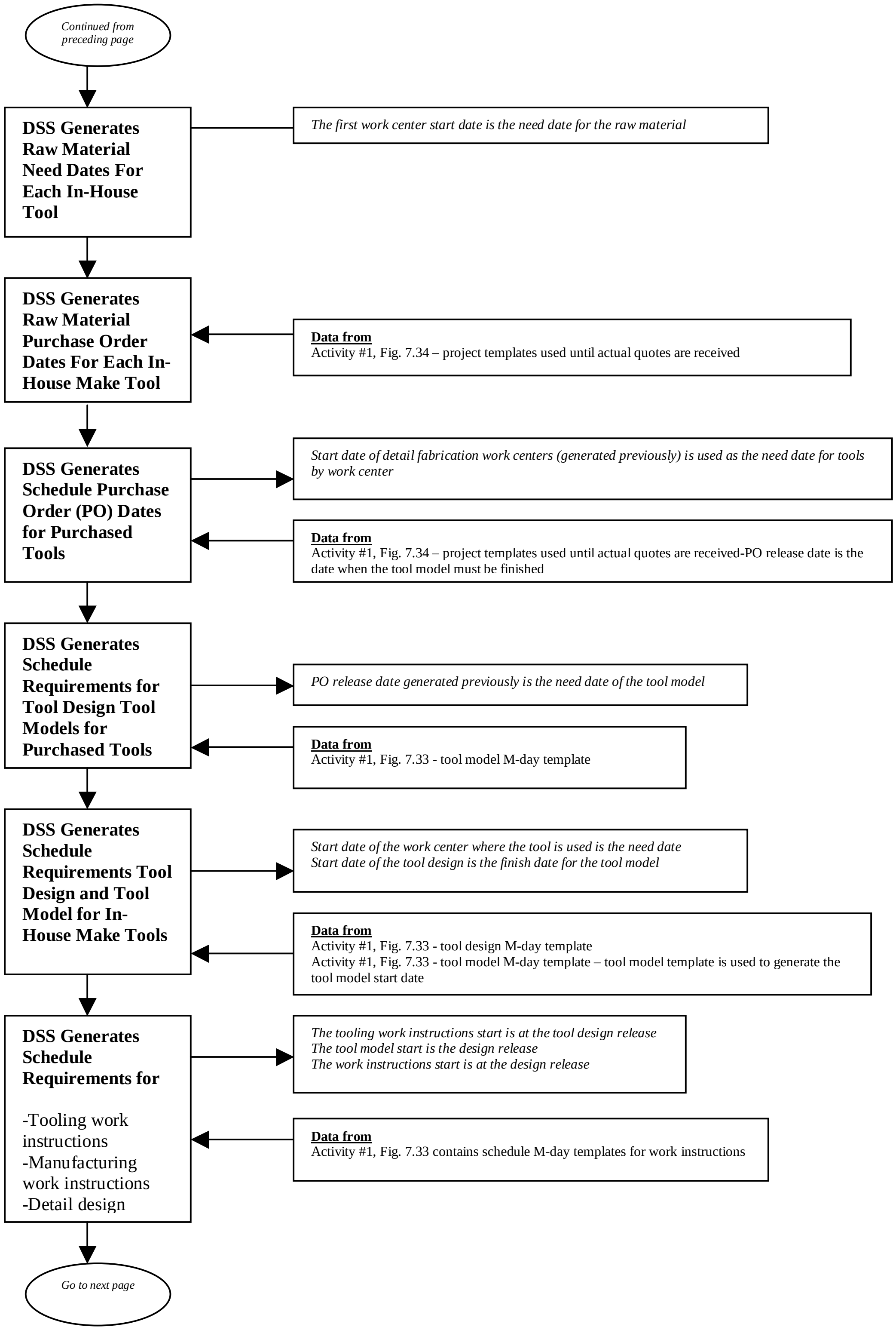
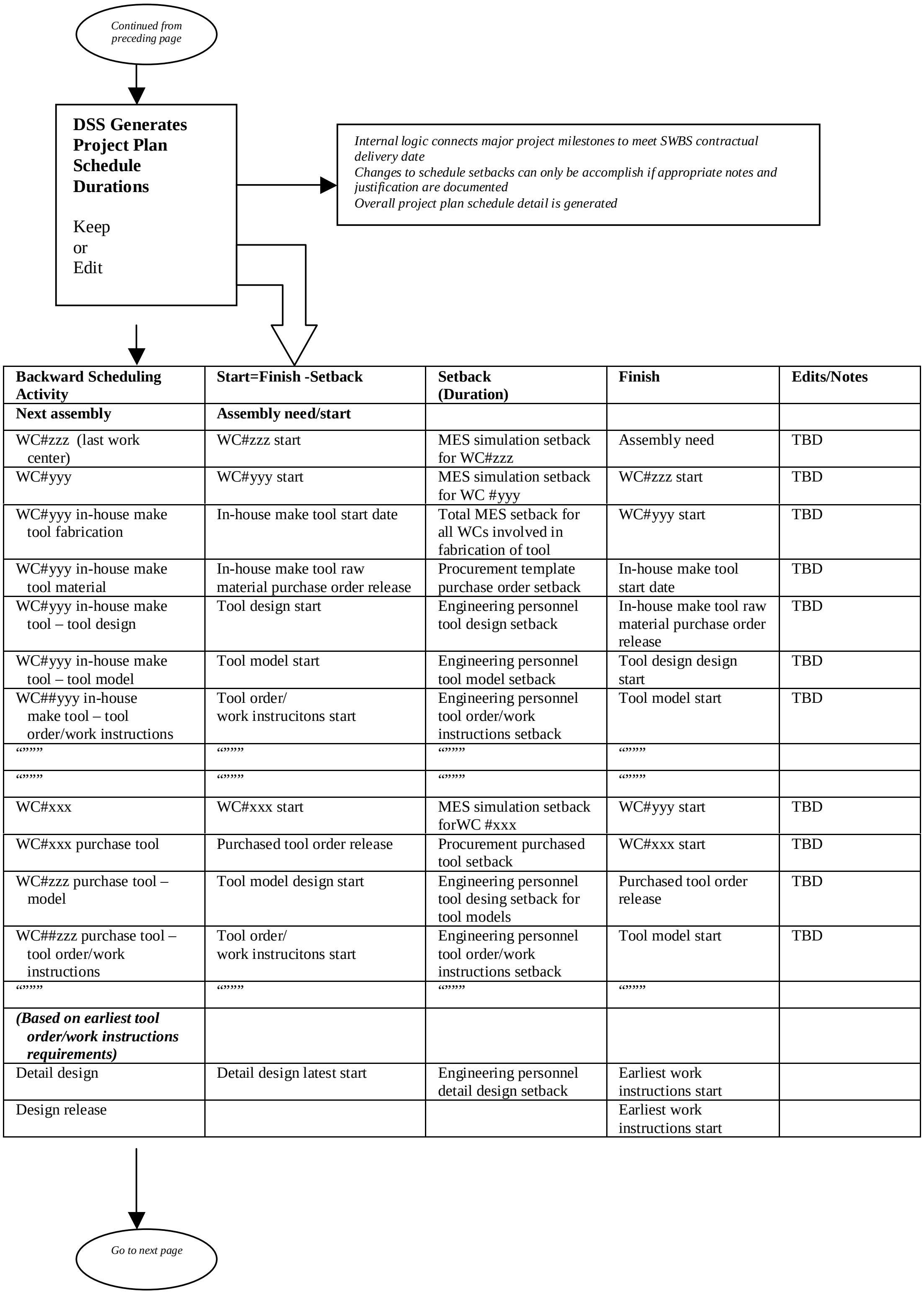


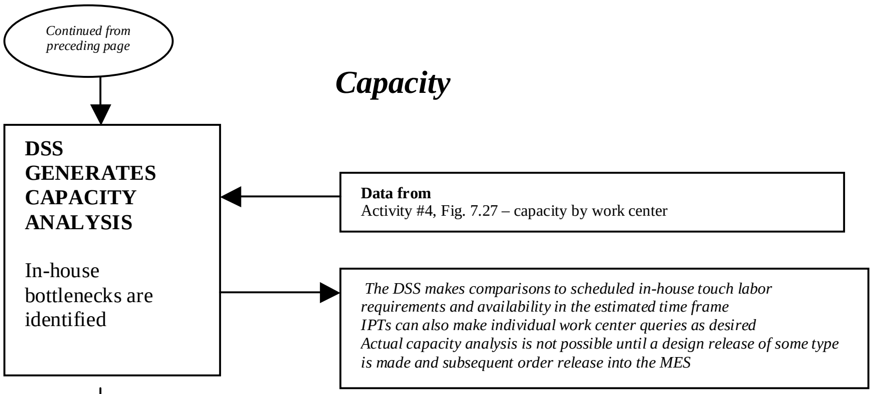
Figure 6.11 Flow Diagram of DSS Operation: 6 of 11



Internal logic connects major project milestones to meet SWBS contractual delivery date
Changes to schedule setbacks can only be accomplish if appropriate notes and justification are documented
Overall project plan schedule detail is generated

Backward Scheduling Activity	**Start=Finish -Setback**	**Setback (Duration)**	**Finish**	**Edits/Notes**
Next assembly	**Assembly need/start**			
WC#zzz (last work center)	WC#zzz start	MES simulation setback for WC#zzz	Assembly need	TBD
WC#yyy	WC#yyy start	MES simulation setback for WC #yyy	WC#zzz start	TBD
WC#yyy in-house make tool fabrication	In-house make tool start date	Total MES setback for all WCs involved in fabrication of tool	WC#yyy start	TBD
WC#yyy in-house make tool material	In-house make tool raw material purchase order release	Procurement template purchase order setback	In-house make tool start date	TBD
WC#yyy in-house make tool – tool design	Tool design start	Engineering personnel tool design setback	In-house make tool raw material purchase order release	TBD
WC#yyy in-house make tool – tool model	Tool model start	Engineering personnel tool model setback	Tool design design start	TBD
WC##yyy in-house make tool – tool order/work instructions	Tool order/ work instrucitons start	Engineering personnel tool order/work instructions setback	Tool model start	TBD
“””	“””	“””	“””	
“””	“””	“””	“””	
WC#xxx	WC#xxx start	MES simulation setback forWC #xxx	WC#yyy start	TBD
WC#xxx purchase tool	Purchased tool order release	Procurement purchased tool setback	WC#xxx start	TBD
WC#zzz purchase tool – model	Tool model design start	Engineering personnel tool desing setback for tool models	Purchased tool order release	TBD
WC##zzz purchase tool – tool order/work instructions	Tool order/ work instrucitons start	Engineering personnel tool order/work instructions setback	Tool model start	TBD
“””	“””	“””	“””	
(Based on earliest tool order/work instructions requirements)				
Detail design	Detail design latest start	Engineering personnel detail design setback	Earliest work instructions start	
Design release			Earliest work instructions start	

Figure 6.12 Flow Diagram of DSS Operation: 7 of 11



Cost

In order to determine an appropriate value for ***cost*** in dollars, a timeframe of occurrence/expenditure is required. Rates and factors are typically applied at the accounting month level. If a task is performed in a timeframe later than originally forecast, then original cost estimates are no longer valid, and changes typically result in increases.

Similarly, if the schedule for a design's manufacture is assumed achievable without appropriate MES line balancing, then a significant management task is overlooked and the resulting forecast is likely erroneous, potentially leading to increases in cost. Until the manufacturing line is balanced, the actual schedule dates for a design's manufacture cannot be accurately determined. Line balancing should occur for each task using backward scheduling to the engineering design task and its associated release date - for touch labor fabrication and assembly tasks alone. Proper line balancing requires a:

1) Detailed assembly load sequence for each design
2) Detailed fabrication sequence for each design
3) Detailed task completion sequence for other support tasks for each design
4) Compilation of a significant amount of design related information forecasts at the component and/or aircraft level, such as:
    a. Assembly design installation drawings
    b. MES fabrication capacity
    c. Vendor quotes
    d. Direct support level (all tasks cannot be accomplished at once)

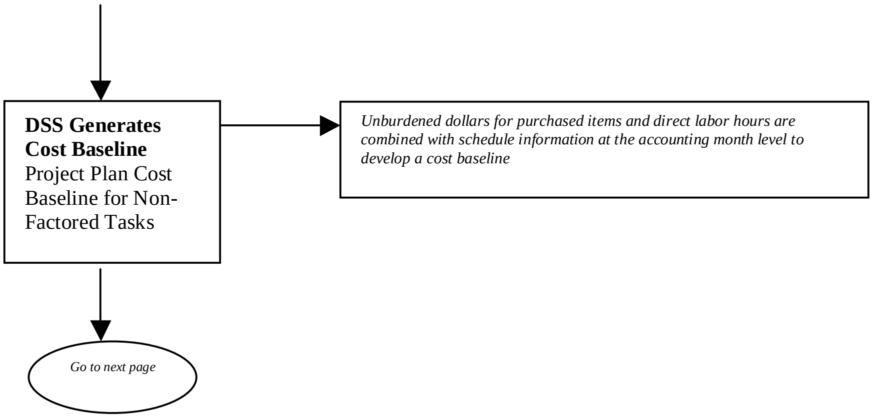
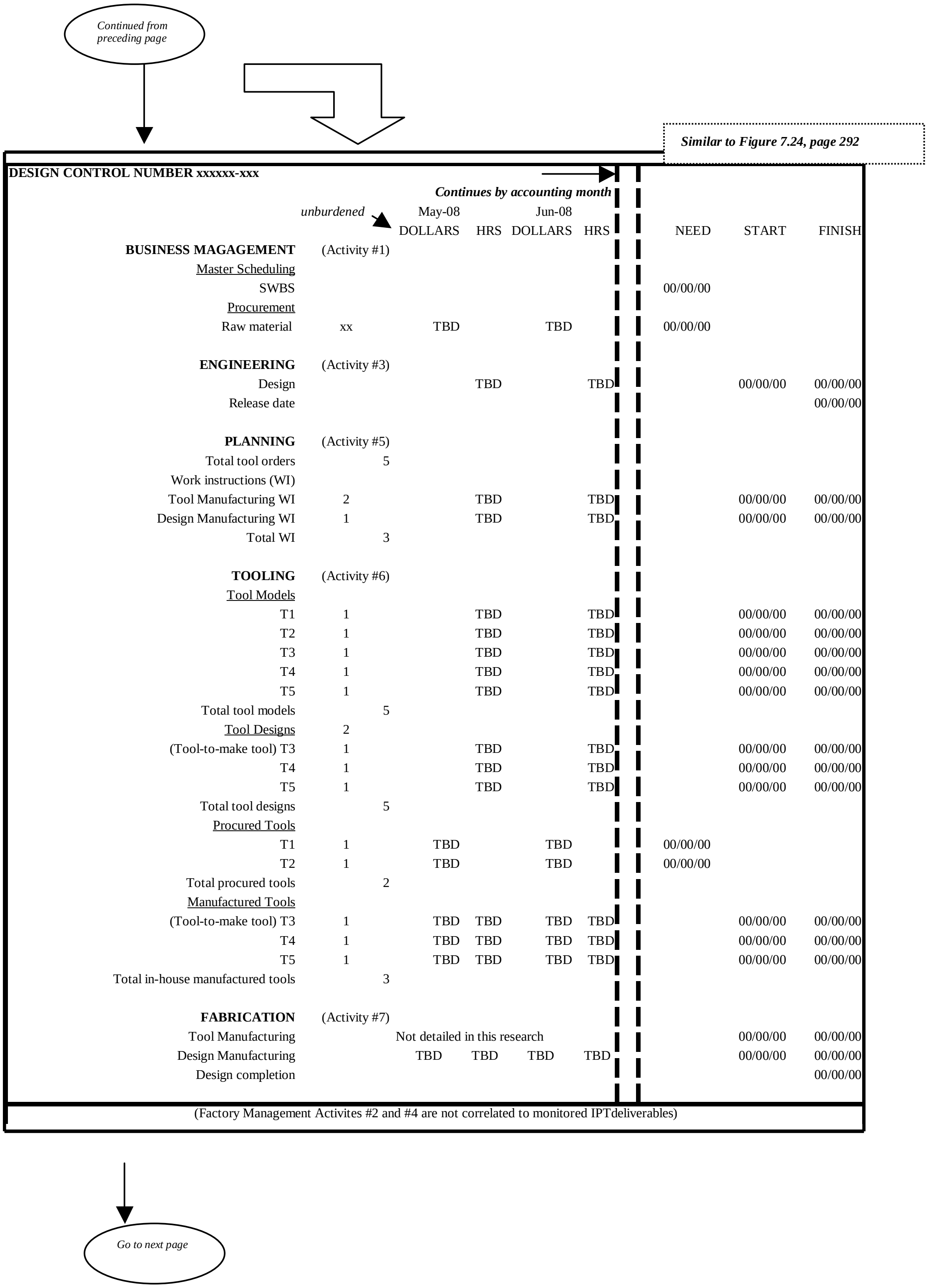


Figure 6.13 Flow Diagram of DSS Operation: 8 of 11



DESIGN CONTROL NUMBER xxxxxx-xxx

			May-08 DOLLARS	May-08 HRS	Jun-08 DOLLARS	Jun-08 HRS	NEED	START	FINISH
BUSINESS MAGAGEMENT	(Activity #1)								
Master Scheduling									
SWBS							00/00/00		
Procurement									
Raw material	xx		TBD		TBD		00/00/00		
ENGINEERING	(Activity #3)								
Design				TBD		TBD		00/00/00	00/00/00
Release date									00/00/00
PLANNING	(Activity #5)								
Total tool orders		5							
Work instructions (WI)									
Tool Manufacturing WI	2			TBD		TBD		00/00/00	00/00/00
Design Manufacturing WI	1			TBD		TBD		00/00/00	00/00/00
Total WI		3							
TOOLING	(Activity #6)								
Tool Models									
T1	1			TBD		TBD		00/00/00	00/00/00
T2	1			TBD		TBD		00/00/00	00/00/00
T3	1			TBD		TBD		00/00/00	00/00/00
T4	1			TBD		TBD		00/00/00	00/00/00
T5	1			TBD		TBD		00/00/00	00/00/00
Total tool models		5							
Tool Designs	2								
(Tool-to-make tool) T3	1			TBD		TBD		00/00/00	00/00/00
T4	1			TBD		TBD		00/00/00	00/00/00
T5	1			TBD		TBD		00/00/00	00/00/00
Total tool designs		5							
Procured Tools									
T1	1		TBD		TBD		00/00/00		
T2	1		TBD		TBD		00/00/00		
Total procured tools		2							
Manufactured Tools									
(Tool-to-make tool) T3	1		TBD	TBD	TBD	TBD		00/00/00	00/00/00
T4	1		TBD	TBD	TBD	TBD		00/00/00	00/00/00
T5	1		TBD	TBD	TBD	TBD		00/00/00	00/00/00
Total in-house manufactured tools		3							
FABRICATION	(Activity #7)								
Tool Manufacturing			Not detailed in this research					00/00/00	00/00/00
Design Manufacturing			TBD	TBD	TBD	TBD		00/00/00	00/00/00
Design completion									00/00/00

(Factory Management Activites #2 and #4 are not correlated to monitored IPTdeliverables)

Figure 6.14 Flow Diagram of DSS Operation: 9 of 11

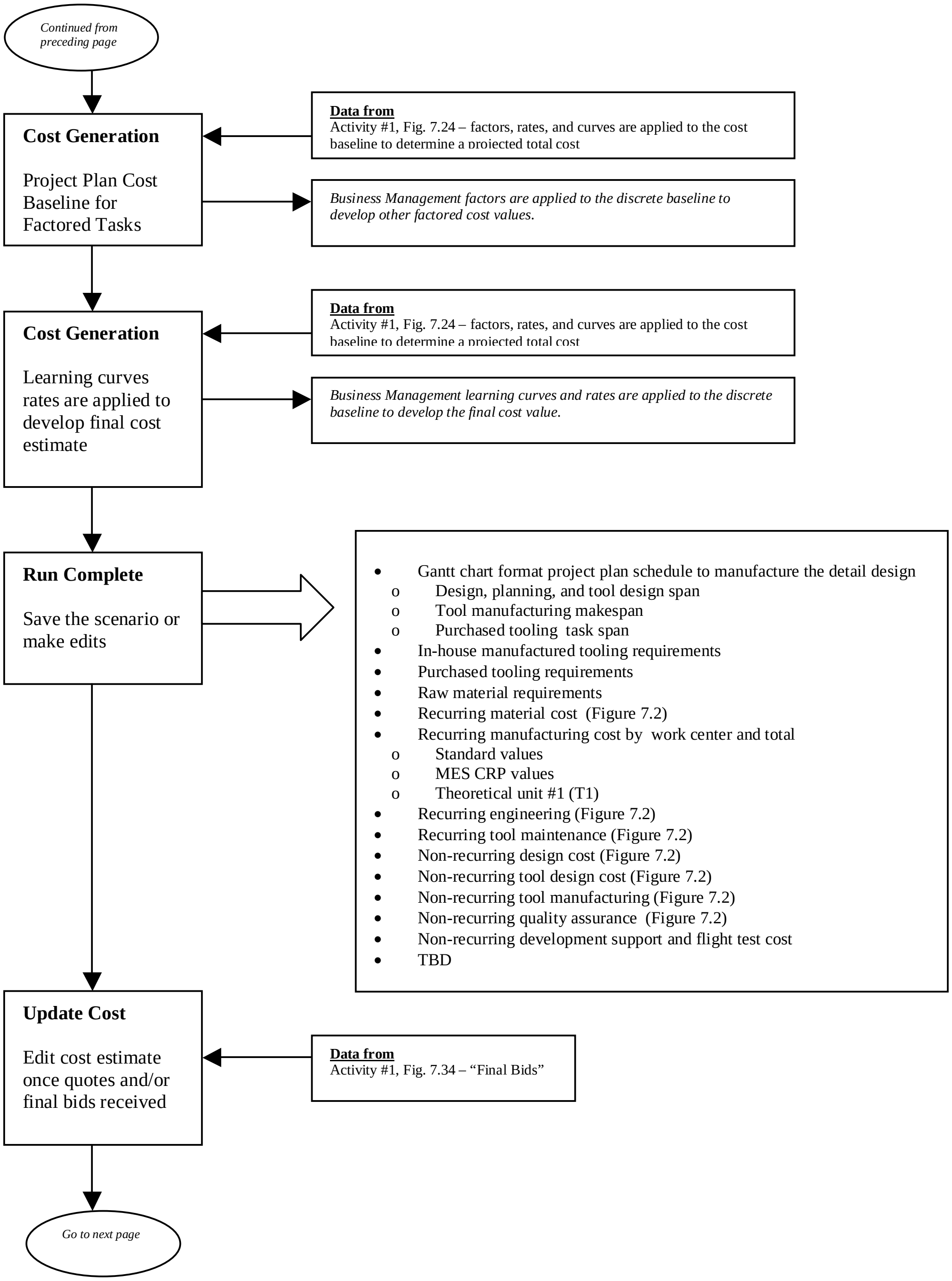


Figure 6.15 Flow Diagram of DSS Operation: 10 of 11

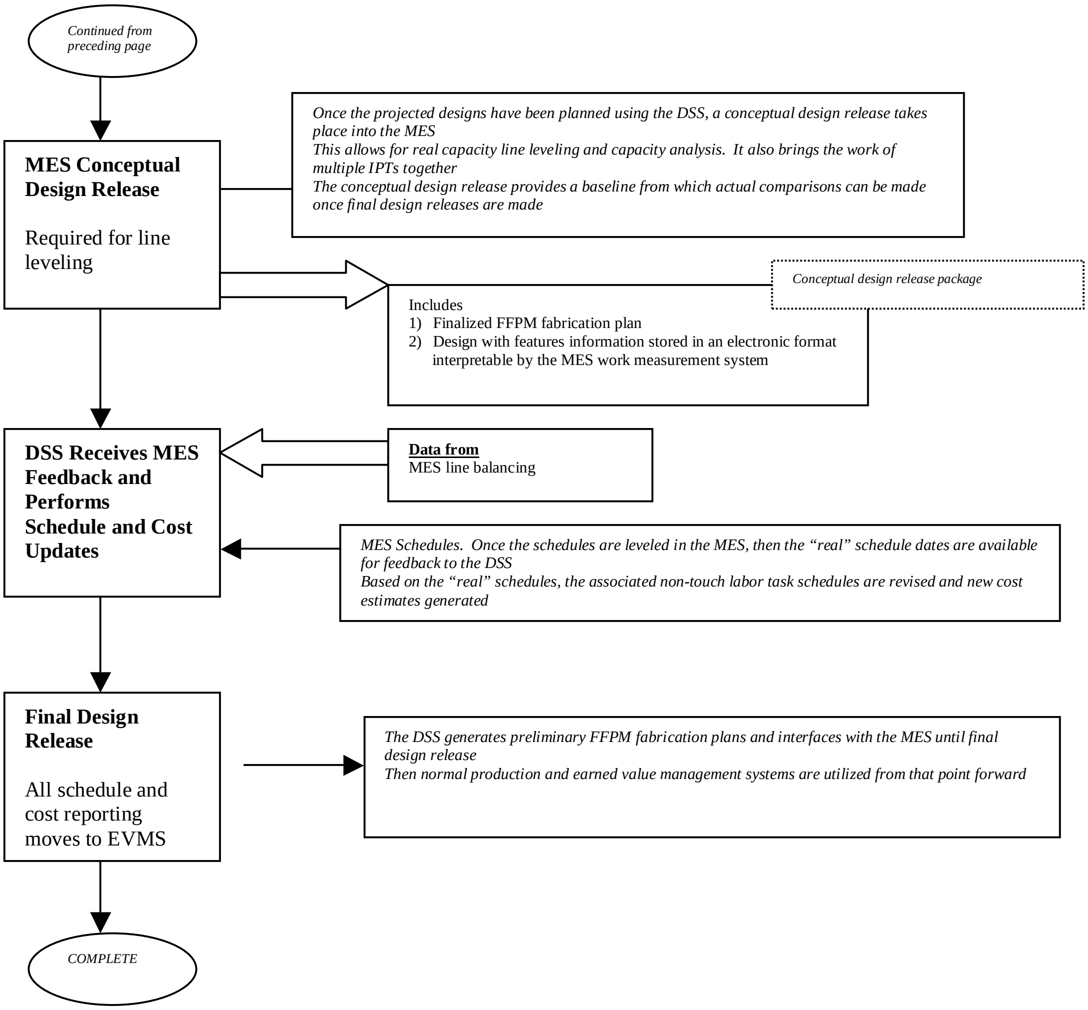


Figure 6.16 Flow Diagram of DSS Operation: 11 of 11

In the next chapter, comparisons between the DSS offered in this research and other decision support approaches found in the literature are presented.

CHAPTER VII

THE CONCEPTUAL FRAMEWORK FOR THE RIM-BASED DSS APPLIED TO THE DESIGN OF AN AIRCRAFT BULKHEAD

This chapter presents the conceptual framework for developing the envisioned reciprocal interdependencies management (RIM) based decision support system (DSS). Chapter 7 does not contain the entire effort required by an enterprise to develop an operational DSS. Instead, Chapter 7 provides a large cross-section of the required information development, which correlates to the executive summary conceptual architecture and utilization instance flow diagrams in Chapter 6.

In Chapter 7, RIM concepts of commonality and selection anticipation are used to create RIM-diagrams for feedforward planning. These RIM-diagrams are then translated into conceptual information hierarchies of commonality information (i.e., databases and systems) the enterprise develops, maintains, and the IPT reuses for early design decision making. In addition, where appropriate, Verganti’s findings and other research findings are interjected into the presentation to validate the need for certain types of information.

RIM-diagrams are not attributed to Verganti, and are instead a contribution of this research in the context of RIM application strategies. RIM-diagramming offers more detail with regard to the technical complexities of early design decision making than is currently documented in the literature.

RIM-diagramming was “discovered” by coupling Verganti’s high-level concepts of RIM with the information requirements of a typical IPT within the context of aircraft manufacturing. In general, RIM-diagrams have a far left column for the reciprocal interdependencies (knowledge links) of technical, resources, and sequencing; and then other columns to the right labeled “commonality” or “common” and “new.” RIM-diagrams help to organize knowledge more meaningfully and highlight that knowledge of new design endeavors is never really at zero percent as suggested in Figure 4.1, page 103. RIM-diagramming will become clearer later in this chapter when examples are provided.

It is important to note that Verganti does not specifically explain how to apply RIM concepts, feedforward planning, selective anticipation, etc. Instead, this author extrapolates from and elaborates upon Verganti’s high-level findings. The conceptual framework presented in this chapter identifies the broad content of the systems architecture, some of the envisioned systems changes, and a general course of action to develop a RIM-based DSS for the specific process of NC machining an aircraft bulkhead.

The ideas of common knowledge and knowledge reuse are not new. Much of the literature in Chapter 3 mentions these ideas; but they are lacking in explanation as to how to accomplish these ends. In most cases, software descriptions and functionality are in the forefront and the underlying data development and technical knowledge correlation are afterthoughts. (As Chapter 7 illustrates, the detail-level work to accomplish these goals is excruciating.)

This author is not suggesting the framework outlined in this research is the only way to approach assembling the extremely large enterprise information “jigsaw puzzle” required for meeting all of the information requirements of an IPT. Instead, this conceptual framework is one way to systematically approach the undertaking and its presentation offers more technical information than is typically available.

7.1 The Basic Approach

In order to define a DSS for an aircraft manufacturing enterprise within the context of RIM, a starting point for assembling the enterprise information "jigsaw puzzle" is selected where minimal changes are expected to be required. The starting point for this application is a baseline where the tools for managing reciprocal interdependencies already exist to a great degree, and only need to be examined within the context of RIM. Once the baseline information is established, RIM concepts and RIM-diagramming are used to progressively move into less defined areas of aircraft conceptual design decision making knowledge.

The first discussion/application of RIM is in the context of project management, and is presented in the next section.

7.2 Project Management and RIM

Multiple reciprocal interdependencies exist within the enterprise with regard to project management knowledge and information. Many widely accepted project management (PM) tools that manage reciprocal interdependencies already exist within aircraft manufacturing enterprises. Examples of these tools are the product structure, work breakdown structure, and cost breakdown structure. Even though these tools may be thought of as having some other function, the underlying reason they exist is to manage reciprocal interdependencies. RIM approaches offer a different way to view these tools, and hopefully improve their use. Table 7.1 is offered as the starting point for using RIM-based strategies to develop a DSS for use during conceptual design. Table 7.1 is at a very high-level and is not intended to illustrate all possible relationships. In addition, the discussion of Table 7.1 is at a very high-level only, and not every entry in each cell is fully explained. More detailed discussed is provided for subsequent RIM-diagrams.

Table 7.1 RIM-Diagram for High-Level Project Management Tools

Reciprocal Interdependencies PM Tools	**COMMON** (Past Designs and Past Processes)	**NEW**
TECHNICAL		
Translation mismatches Design Engineering	*Features not uniformly defined* Features Product Structure EBOM	Very similar
Planning and Factory Management	MBOM Features Processes	Organization of information is unlikely to change for in-house processes
Control Processes and Tools Business Management	SOW/WBS/CBS (high-level)	
Planning, Factory Management, or Fabrication	MBOM Features Process availability information is organized in CBS Translated to work instructions (WI) by the planner	Organization of information unlikely to change for in-house processes Some change may occur for new process or vendors
RESOURCES		
Business Management *Potential mismatch*	SOW/WBS Make or Buy Policy Requirements forecasts *Budgeted hours* Procurement contracts CBS & WBS (high-level)	Organization of information is unlikely to change
Factory Management, Planning, or Fabrication	In-house CBS (low-level) Routing on (WI) MES work measurement loading *Staffing plans*	Some change may occur for new process or vendors
SEQUENCING		
Business Management *Potential mismatch*	Master Schedule (Deliveries) *Integrated Master Schedule* (high-level SWBS) WBS/CBS (high-level)	Organization of information is unlikely to change
Factory Management, Planning, or Fabrication	Internal schedules by WBS/CBS (low-level) Work instructions by WBS by CBS (low-level) *Schedule translated by MES*	Some change may occur for new process or vendors

The information in the RIM-diagram in Table 7.1 is organized into three columns. The first column represents the reciprocal interdependencies to be managed from the perspective of high-level project management. The second and third columns provide insights into how to manage the reciprocal interdependencies. Commonality items (i.e., as defined in Chapter 1, page 29) are considered in the second "Common" column, and "New" (i.e., non-commonality) items are considered in the third column. The fact that many of the tools listed in Table 7.1 (e.g. SOW, WBS, CBS) are used over and over conveys commonality exists between past and current endeavors in the context of aircraft manufacturing.

In the second column, the cells have a horizontal dashed line to represent how information transfers or transitions within the reciprocal interdependencies. For example, technical engineering information is found in the features, product structure, and engineering bill of material. The engineering bill of material (EBOM) transitions to manufacturing, and is used in the form of the manufacturing bill of material (MBOM). The features also transfer, in that, they do not substantially change. Another example is found in the reciprocal interdependency titled, "Processes and Tools" in the first column. During the conceptual design phase, information is provided to manufacturing in the SOW, WBS, and CBS (at a high-level). Later, the information transitions by expanding to a lower-level of detail or being used in a different format. For example, once a project progresses to a certain point, the relevance of the SOW is superceded by the lower-level detail translated into the work instructions.

Selective anticipation deals with identification of the *patterns* related to how information is classified and developed by one activity and used by another activity. The most critical patterns of use are those that exist early in the product development lifecycle. Hence, some of highest payoff RIM opportunities exist between engineering and manufacturing in the first segment of Table 7.1 titled "Technical."

In the course of applying concurrent engineering concepts, many organizations have already discovered the need to make MBOM=EBOM. (Johnson, 2007; Ou-Yang and Pei, 1999; Xuebao 2005.) The assumption for the RIM-based DSS being defined by this research is that EBOM=MBOM. This author's work experience validates the needs identified by the aforementioned authors. The following discussion is based on work experience and provides insights as to why the EBOM=MBOM assumption is necessary in the context of developing a system to assist IPT members in decision making.

When EBOM=MBOM, the IPT members must try to figure out the major component assemblies and potential subassemblies at the beginning of the design process and assigns design numbers. The design number is used to control the fabrication of details, plan subassembly kits, and monitor progress once the design is released. EBOM = MBOM makes the management of information more seamless. When EBOM≠MBOM, subassembly design numbers are assigned by manufacturing in the MBOM. This makes it very difficult to automate the exchange of information and keep it up-to-date and error-free.

Even though computer programs can be written to translate the information, invariably, it leads to problems. The subassembly number an operator uses on work instructions does not match a design drawing, and sometimes it takes hours to figure out what to do if the work instructions have a mistake on the detail parts list. Also, the required *translation* between the EBOM and MBOM makes it difficult to incorporate material requirements into the material requirements planning (MRP) systems. Rummler and Brache (1995) describe this type of interface as being where the “baton is passed in the white spaces of an organization chart.” A problem exists because the information could not flow seamlessly without translation.

This author worked on a project during the conceptual design phase where EBOM=MBOM was used. There was tremendous resistance to the approach because it required so much work by the IPTs. Instead of leaving decisions until later when the design was mature, considerable additional effort had to be accomplished using incomplete design information. Some teams were talented at working with sketchy information, but most were not. More teams could have been successful if there had been better tools available and training to help them work with incomplete information.

Referring to the RIM-diagram in Table 7.1, another “Technical” RIM opportunity that has not been fully utilized exists with regard to “features.” The application of commonality and selective anticipation in the context of features offers potential insights into improving decision making, and is an important aspect of this research. Verganti notes the use of expected features to simulate real information in formats recognizable to the teams was one of the most effective strategies. Features are discussed in greater detail later in this chapter in Section 7.8.

Another “Technical” RIM opportunity exists within the context of “Processes.” As “processes” are traced downward in the second column of Table 7.1, the commonality aspect of processes has already been established for in-house manufactured designs. The available processes are found in the Cost Breakdown Structure (CBS). The CBS project management tool exists to facilitate RIM from a commonality perspective - even if it has not been identified in this context before. However, from the perspective of selective anticipation, the RIM-based strategy conveys the information used in the CBS requires a defined *pattern of use*. (These *patterns of use* are systematically developed as this research applies RIM strategies throughout Chapter 7.) Again, from the perspective of project management tools (e.g., WBS, CBS, and product structure) their use and availability is well documented in the literature. RIM-based strategies provide a way to consider these tools from a different perspective and identify lower-level detail patterns of use related to knowledge exchange.

Another RIM opportunity exists with regard to the combination of “Technical” Features and “Technical” Processes in Table 7.1. As one surveys the middle column of Table 7.1, the “Technical” Features information transitions via the process availability information organization by CBS and the planner’s translation of features into work instructions. Developing a consistent definition of features and a structured approach in applying features knowledge offers the potential to convert expert knowledge available to common knowledge.

In the last segment of Table 7.1, “Sequencing” RIM opportunities are considered with regard to how the Master Schedule is translated by the manufacturing execution system (MES). The information above the horizontal dashed line is different from the information below the dash line and a clearly defined knowledge link during early design is needed - but not defined. If one surveys the information from top to bottom in the middle column, then it becomes apparent that one way to develop the knowledge link is by using the information available from other sources. In particular, the “Technical” information related to “Features” and “Processes.”

The conceptual framework for developing the RIM-based DSS assumes several project management tools mentioned above are used (basically) in their existing formats as a starting point. As discussed in earlier chapters, there is room for improvement with regard to how these tools are initially created, but these improvements are not anticipated to significantly impact this conceptual framework as a whole. There can be some variation between the product structure, high-level cost breakdown structure, and low-level cost breakdown structure presented here and the actual structures used in a specific real world enterprise. These variations are typically driven by management preferences and are not envisioned to cause a problem with regard to developing an operational DSS based on the conceptual framework presented.

In the next two sections, conceptual information hierarchies for tools listed in the commonality column of Table 7.1 - product structure and CBS - are discussed. In subsequent sections, additional items listed in Table 7.1 are further defined. However, complete information hierarchies are not presented and emphasis is on information dealing with NC machining of an aircraft bulkhead.

7.3 Product Structure

Product structures have been used in the aircraft industry for many years. More technical information related to product structures is provided in Appendix B. The product structure is controlled by the Engineering activity (i.e., IDEF0 diagram Activity 3, Figure 2.5, page 54). The conceptual information hierarchies of the product structure for an aircraft enterprise in the RIM-based DSS are as follows:

- Airframe
    - Fuselage
        - Components (forward, center, aft, etc.)
            - Subassemblies
                - Details (bulkhead, frame, floor, etc.)
    - Wing
        - Components
            - Subassemblies (combinations of details)
                - Details (spars, skins, ribs, etc.)
    - Empennage
        - Horizontal stabilizers
            - Components
                - Subassemblies
                    - Details
        - Vertical tail
            - Components
                - Subassemblies
                    - Details
- TBD

Figure 7.1 Conceptual Product Structure Information Hierarchies

Assumptions related to the product structure in the context of the RIM-based DSS are as follows: 1) EBOM=MBOM and 2) nomenclature (naming) of detail designs is defined based on commonality, is consistent, and a part of the electronic record of the product data management system (PDMS).

7.4 Cost Breakdown Structure

Cost breakdown structures (CBSs) have been used in the aircraft industry for many years. More technical information related to CBSs is provided in Appendix B. The CBS is controlled by the Business Management activity (i.e., IDEF0 diagram Activity 1, Figure 2.4, page 53) and used by the enterprise to organize information for estimating, developing budget distributions, collecting actual performance data, controlling cost, and reporting contractual cost information to the customer. Hence, the cost breakdown structure must be "linkable" to the WBS at some level. However, as long as the CBS meets higher-level external reporting needs, there is flexibility in the CBS to meet the lower-level information needs of the internal users.

Each CBS level has both a unique number and descriptive identifier. The CBS work center numbering system is used to relate various databases within the enterprise. The verbal description is used to help users understand the content.

The next two sections, 7.4.1 and 7.4.2, deal with high-level and low-level segments of the CBS. These sections are offered to: 1) give the reader an overview of the general ways in which "cost" is defined within an aircraft manufacturing enterprise and 2) provide the conceptual approach used in this research from both high-level and low-level CBS perspectives. (Note the RIM-diagram in Table 7.1 does not provide lower-level detail and remains a high-level only.)

7.4.1 High–Level Cost Breakdown Structure

The conceptual information hierarchies of the high-level CBS for an aircraft manufacturing enterprise in the DSS are as follows:

- Aircraft System Cost
    - Engineering
        - Design (Nonrecurring) [designer]
        - Recurring
    - Tooling
        - Nonrecurring (1st article & rate tooling)
            - Tool design
                - Tool design [tool designer]
                - Work instructions [planner]
                - Tool engineering [manufacturing engineer]
            - Tool manufacturing
                - Tooling material
                - Tooling labor
        - Recurring (sustaining tool maintenance)
    - Quality
        - Nonrecurring quality assurance
        - Recurring inspection and test
    - Recurring Production
        - Manufacturing
            - Manufacturing material
                - Material direct
                - Material indirect [purchasing representative]
            - Manufacturing overhead
                - Manufacturing indirect [industrial engineer]
            - Manufacturing labor
                - Manufacturing direct [touch labor]
                - Manufacturing indirect [manufacturing supervision and direct support; manufacturing representatives]
    - Project Management
        - Other [other cost engineers]
    - TBD
    - TBD

Figure 7.2 Conceptual High-Level Cost Breakdown Structure Information Hierarchies

A typical cost category where IPT members charge their labor to a contract is denoted in brackets in Figure 7.2.

The assumptions related to the high-level CBS within the RIM-based DSS are as follows:

1) The high-level structure utilized by the DSS matches the actual structure the enterprise uses
2) Direct labor requirements are estimated using feature-based relationships (discussed later in Section 7.10)
3) Direct material and tooling requirements are estimated using feature-based relationships (discussed later in Section 7.8.2)
4) IPTs use the platform provided within the DSS as opposed to developing their own worksheets to calculate this type of cost

The high-level CBS is used to accommodate the needs of information exchange with the customer and the traditional aircraft estimating process. Once lower-level estimating work is accomplished, the "total cost" estimate is accumulated into a customary high-level format using generally accepted terminologies, like "recurring and nonrecurring."

The organization of data at the highest level varies among enterprises based on their internal definitions of engineering, tooling, and manufacturing. For example, in some enterprises the tasks of manufacturing engineering effort and the tool design effort are organized under the higher-level category of nonrecurring engineering. To a great degree, these nuances do not matter as long as the labor charges associated with the design engineering effort is separable from the manufacturing engineering effort and so forth. If the lower-level details of a cost information hierarchy are defined, then sorting the information differently is straightforward.

Much research is devoted to the cost visibility problems associated with the methodologies used in the traditional high-level CBS illustrated, but this segment of RIM-based DSS information development is assumed to be in the traditional format for simplicity. (Traditional formats are discussed in Appendix B.) The emphasis of this research is toward developing information at a lower-level of detail, so this assumption does not significantly impact the overall outcomes. The next section discusses the lower-level cost breakdown structure.

7.4.2 Lower–Level Cost Breakdown Structure

The high-level CBS illustrated in Figure 7.2 is typically allocated into smaller segments to develop a lower-level CBS. The lower-level CBS is used for internal information management, i.e., the collection of direct labor charges, organizing personnel and departments, routing jobs, etc. In this research the lower-level CBS used for routing jobs and cumulating labor charges by process is referred to as the CBS "work center" level. (The name "work center" is a discretionary identification in that it is not being represented as an industry-wide term. Most companies have their own naming conventions for different levels of a CBS.)

There are many ways to establish a lower-level CBS for a Fabrication activity (i.e., IDEF0 diagram Activity 7, Figure 2.7, page 56). The CBS organization depends on the enterprise strategy for use (and reuse) of cost information. In the next two figures, Figure 7.3 and 7.4, conceptual lower-level CBS information hierarchies are presented. Figure 7.3 illustrates segments of the CBS not related to "Detail Fabrication." This figure is considered a placeholder, in that, the emphasis of this research is on "Detail

Fabrication" processes used in producing a NC machined aircraft bulkhead. Figure 7.4 illustrates the lower-level CBS for "Detail Fabrication," which includes the in-house processes used to complete a design shaped by NC machining. The work center level of the information hierarchies is denoted in blue italics in Figure 7.4

- Final Assembly
    - Mate & Complete
    - Paint
- Component Assembly
    - (multiple levels for structure and systems)
- Mechanical Subassembly
    - (multiple levels)
- Special Fabrication and Subassembly
    - Welding
        - Electron Beam
        - Laser Beam
    - Electrical Components (Electrical)
        - Harnesses
        - Cables
    - Tubing and Ducts (Plumbing)
        - Tubing & duct fabrication
        - Tubing & duct assembly
    - Other….

Figure 7.3 Lower-Level CBS Information Hierarchies Not Related to Detail Fabrication

- Detail Fabrication
  - Composites Fabrication
    - TBD (hierarchies not defined or discussed)
  - Sheet Metal Fabrication
    - TBD (hierarchies not defined or discussed)
  - NC Milling and Support **[Group 1 of 9]**
    - NC Milling
      - 3-Axis milling *(work center level)*
      - 5-Axis milling
      - 5-Axis high speed milling
    - Specialty Hole Processing (Equipment) **[Group 2 of 9]**
      - Drilling/Boring type 1 *(work center level)*
      - Drilling/Boring type 2
      - 3-Axis (tooling holes)
    - Minor Subassembly for NC Machined Parts [Not discussed]
      - Hole processing *(work center level)*
      - Bushing installation
      - Nutplate installation
    - Hand Finish **[Group 3 of 9]**
      - Vapor degrease *(work center level)*
      - Deburr
      - Hole processing (portable systems)
      - Tooling tab removal
  - Coatings **[Group 4 of 9]**
    - Wash/Clean *(work center level)*
    - Mask
    - Prime
    - Paint
    - Electrical bonding
    - Seal bonding (not discussed)
  - Hardening and/or Special Treatment **[Group 5 of 9]**
    - Wash/Clean *(work center level)*
    - Heat treat
    - Heat treat age
  - Chemical Processing **[Group 6 of 9]**
    - Wash/Clean *(work center level)*
    - Chemical milling
    - Annodize
    - Plating
  - Forming **[Group 7 of 9]**
    - Wash/Clean *(work center level)*
    - Shot peen
  - Marking [**Group 8 of 9]**
    - Stamping *(work center level)*
    - Vibroengrave
- Detail Fabrication Quality Assurance [**Group 9 of 9]**
  - Plate inspection
  - Intermediate inspection
  - Non-destructive testing
  - Final inspection
  - TBD

Note: each CBS description also has a unique numerical identifier used by various enterprise systems to relate the lower-level CBS to higher levels of the CBS, departmental budgets, planning routes, work measurement studies, MES scheduling logic, etc. In many instances the CBS work center number is used by the DSS for similar purposes. As much as possible the DSS seeks to emulate/imitate enterprise systems the IPTs may have some familiarity with.

Figure 7.4 Lower-Level CBS Information Hierarchies for Detail Fabrication

The assumptions related to the lower-level CBS within the RIM-based DSS are as follows:

1) The overall CBS structure is based on the the EBOM=MBOM philosophy (Detail fabrication, Subassembly, Assembly). However, some variation may occur for manufacturing preferences, but these will be limited.

2) The work center in the detail fabrication CBS is the baseline for assessing process capabilities. The work center grouping in the detail fabrication CBS reflects how processes are managed for the consideration of similar types of labor classifications, etc.

3) The detail fabrication CBS work center number is used to route jobs based on work instructions.

4) Capacity information is organized at the CBS work center level for detail fabrication. It is expressed relative to shifts, personnel, and equipment over a forecasted timeframe based on the M-day and accounting month calendar provided by Business Management. This information is used to assess labor and machine hours availability in a given time frame.

A brief explanation of the rationale behind the CBS in Figures 7.3 and 7.4 is offered.

In Figure 7.3, “Final Assembly, Component Assembly, and Mechanical Subassembly” are considered to be self-explanatory. “Special Fabrication and Subassembly” processes are those joining details, wires, and/or hardware; but do not involve “traditional” mechanical assembly using rivets, bolts, or other fasteners. Work areas dedicated to electrical harnesses and tubing manufacture are specialized in both their fabrication and assembly equipment and procedures. Also, the persons performing these tasks typically hold a unique classification or certification.

In Figure 7.4, the “Detail Fabrication” information hierarchies are organized to simultaneously facilitate the method in which the design is conveyed (i.e., the drawing type - detail, next assembly, installation drawing) similarities of processes, equipment utilization, and worker assignments. Work centers are designated in parentheses.

“Composites Fabrication” is used to segregate composite related work centers from traditional “Metal Fabrication” work centers. “Composites Fabrication” and “Sheet Metal Fabrication” are not discussed in this research.

In Figure 7.4, the “NC Milling” group of work centers is where plate preparation and major milling (i.e., shaping) are accomplished. The work center designated as 3-Axis milling is where plate surfaces are prepared and simple designs are milled.

“Specialty Hole Processing” is the group of work centers where specialized hole processing equipment resides, and typically this equipment has hole processing capabilities beyond that of the major NC milling machines. Also, when the amount of hole processing reaches a certain level, then the decision is typically made to perform the hole processing in these work centers to “free up” the NC milling machine to start the next job. The “Special Hole Processing” equipment may or may not be dedicated to designs that are shaped by NC milling. These work centers could also have composite designs routed to them. These types of factory policies are driven by management decision, and the important information in the context of IPT decision making is awareness of the policies in place. These types of factory policies information typically reside in some form (i.e., either expert knowledge or written policies) within the Factory Management and Planning activities (i.e., IDEF0 diagram Activities 4 and 5, Figures 2.5 and 2.6, pages 54 and 55).

“Minor Subassembly for NC Machined Parts” is an exception because “subassembly” is being performed in “Detail Fabrication.” There are instances where bulkheads, frames, and other NC machined details require bushings or nutplates to be installed prior to assembly with other major structural details, and these installations are reflected on subassembly drawings. For these types of simple installation drawings (e.g., bushing and nutplates installed on a bulkhead), manufacturing often prefers to maintain a dedicated work area within "Detail Fabrication." (Note that this segment of the lower-level CBS is provided for information only. For this research, only detail designs/drawings are being considered by the IPT utilizing the DSS. Subassembly and installation drawings are not being considered.)

In Figure 7.4, "Hand Finish" involves cleaning parts, checking for burrs, removing tooling tabs, and minor hole processing (e.g., rework/repair) with portable systems. NC machined details are assumed to be processed by teams of workers, some assigned to NC machines and others assigned to "Hand Finish." It is assumed more experienced machinists are operating the machines, but perform other tasks as needed if work is unavailable.

The processes in "Coatings" are grouped because of similar environments and the likelihood of similar worker classification/certification. These processes located "lower" in the assembly sequence because, in most cases, they are best performed prior to subassembly. (Note that "Seal bonding" is not used on NC machined details, so this process is not discussed or diagrammed in later sections.)

In order to have cost visibility at different levels, the CBS has to recognize these levels. For example, in order to have improved cost visibility of the "Masking" process versus the "Painting" process, the tasks and labor charging should be designated differently via the work center designations in the CBS. In addition, by identifying and scheduling "Masking" separate from "Painting," it facilitates concurrent scheduling of the tasks on different jobs, i.e., the start of "Masking" on a second job can be scheduled prior to the completion of "Painting" on a first job. If enterprise management desires to segregate the CBS to a lower-level, then it typically can be accomplished; provided the Business Management activity approves.

"Hardening," "Chemical Processing," and "Forming" are included in Detail Fabrication and segregated due to: 1) the technical requirements of the processes, 2) the preference to independently sequence and manage their occurrence, or 3) the desire to perform these tasks prior to assembly. It is not preferable to load a design in an assembly fixture and subsequently unload it for routing back to Detail Fabrication.

In Figure 7.4, "Marking" processes include ink stamping control number on detail designs and vibroengraving serial numbers onto detail designs. Marking is used to control inventory and configuration. Some type of "Marking" is typically required on each processed design. Some designs are only marked upon completion; but critical designs, such as "fracture critical" bulkheads, are serialized (i.e., uniquely assigned) to a specific aircraft, and are closely monitored. Personnel performing marking tasks are assumed to travel throughout departments, and are either a different classification or a different experience level (i.e., the best machinists are not assigned to perform marking tasks).

The "Detail Fabrication Quality Assurance" group of work centers deals with inspection processes.

From the perspective of the conceptual framework, the following assumptions are being made: 1) process capabilities for in-house processes are relatable via the lower-level CBS at the work center level and 2) the work center level is the lowest level of the information hierarchies for “Detail Fabrication.” In the next section, a RIM-based approach is used to discuss the definition of “capability" within the context of the conceptual framework.

7.5 Detail Fabrication Capability

In this section, RIM is used to discuss *capability*. While capability is mentioned in a great deal of available literature, it is typically not clearly defined. One of the tasks associated with developing a conceptual framework is the systematic definition of capability. This section provides the explanation of capability in relation to development of a conceptual framework for a RIM-based DSS.

First, a general discussion of common interpretations of capability is presented in three contexts: 1) technical, 2) resources (management strategy), and 3 sequencing (availability/scheduling), using “hole processing systems” as an example. These three contexts match the reciprocal interdependencies previously listed in Table 7.1, page 175.

Second, a RIM-diagram is offered to provide additional insights into the use of commonality and selective anticipation to facilitate the development of a DSS within the three contexts of capability. Lastly, the conceptual approach used to address capability within the envisioned DSS is presented.

7.5.1 Hole Processing Systems Capability – Context 1: Technical

One context of hole processing capability is based on the technical differences between hole processing systems. Hole processing systems are defined as combinations of people and portable tools, small machines, non-design tooling, design tooling, and specialized machines required to process holes.

The typical design features used to compare hole processing systems are material, hole diameter, thickness, tolerance on hole diameter, and tolerance on hole location. Because certain in-house hole processing systems have been used on past designs - certain technical information regarding capability of hole processing systems is available (due to commonality) and is organized (or unfortunately, disorganized) in various ways in the enterprise.

One way in which hole processing systems technical information and associated relationships have been utilized on past designs is illustrated in the following statements:

1) A worker can only process certain holes "by hand" based on the capabilities of the hand-processing systems available. These capabilities are expressed in terms of some combination of design features:
    a. If the tolerance on hole diameter requirement reaches specified limits, then tooling is required.
        i. This tooling requirement can generate a second tooling requirement. (Tools to make tools.)
            1. If the tolerance on hole reaches another specified limit, then specialized hole processing machines are utilized.
    b. If the material thickness requirement reaches a certain limit, then tooling is required.
        i. This tooling requirement can generate a second tooling requirement. (Tools to make tools.)
            1. If the material thickness reaches another specified limit, then specialize hold processing machines are utilized.

2) Similarly, a worker can only locate a hole within a certain tolerance range using hand-layout procedures.
    a. If the tolerance on hole location requirement reaches a specified limit, then tooling is required.
        i. This tooling requirement can generate another tooling requirement.
            1. If the tolerance on hole location requirement reach a specified limit, special hole processing machines are utilized.

3) Purchased hand-held processing systems have published values associated with their specifications and manufacturing engineering typically performs tests to establish guidelines before the equipment is placed in service.

4) Purchased drilling, reaming, and boring machines have published specifications, and manufacturing engineering typically performs tests to establish guidelines before the equipment is placed in service.

5) Purchased NC milling machines also perform hole processing, the specifications are published, and manufacturing engineering typically performs tests to establish guidelines before the machine is placed in service.

6) A “materials and processes” group typically maintains process information for materials and processes used in the past. In addition, this group organizes MIL-SPECs and MIL-STDs (Department of Defense standardized information) and other information for the enterprise to use.

7) Factory management and workers typically have preferences for the use of one hole processing system instead of another, but this only comes into play once the technical requirements of the job are met. (Preferences are not allowed that do not meet the requirements of M&P specifications.) For example, if two hole processing systems exist in the same department or the same area, and both systems have the capability to meet the requirements, then manufacturing has flexibility.

The preceding statements provide insights into the reciprocal interdependencies related to technical aspects of hole processing capability. Recall the RIM-Diagram in Table 7.1 on page 175. The technical hole processing information represents an example of lower-level detail for the “Technical” reciprocal interdependencies shown on this RIM-diagram.

Another type of technical reciprocal interdependency is related to installation/assembly tolerance. For example, it is easy to understand a designer cannot release drawings where all of the holes are processed in the detail designs of a major component prior to assembly. The detail designs likely would not fit together properly due to assembly tolerances. The reason hole processing capability can exist *away from* *the assembly* in Detail Fabrication is because the designer consciously made the decision some assembly tolerance requirements are to be met in other ways. Hence, the decision for selecting the hole processing system is influenced by assembly tolerance considerations made by the designer. The following statements illustrate the way in which installation relates to hole processing capability:

- In order for holes to be processed using large pieces of specialized equipment in detail fabrication, the consideration of assembly tolerances related to the holes has to be addressed in the assembly sequence. This in turn, establishes whether a control tool is going to be used to locate the detail to the assembly after processing and/or whether the holes processed are going to be used to establish the "hole location" for subsequent details installed.

- When certain assembly tolerance decisions are made, then it affects subsequent decisions on where, how, and when hole processing is accomplished on other details.

- In order to modularize some of the assembly work and concurrently control assembly tolerances, some hole processing is performed with two or more parts together in a subassembly. This is typically accomplished using a hole processing system involving tooling, and by its very nature is performed in subassembly instead of detail fabrication.

- Some hole processing is done during the final stages of assembly because the assembly tolerances have to be reconciled. In aircraft manufacturing, it is not likely that all clips, brackets, supports, etc. can be installed in subassembly because of installation interferences.

- Because hole processing systems are tied to sequencing issues, the same hole processing systems are likely to be found in different locations on the assembly line.

While the above descriptions are intentionally broad and do not cover all of the information required to make technical hole processing systems decisions, the point is being emphasized that a certain aspect of hole processing capability reflects a prior decision related to assembly tolerance - either knowingly or by default. Though this research does not use the constraint of *total assembly tolerance*, intuitively, it makes sense that in order to address the needs of improved conceptual design decision support, more work needs to be done to describe the technical details of this type of information exchange. (An opportunity for future work for this author.)

There are many problems associated with the methods used in the development and application of cost estimating relationships (CERs) dealing with assembly and tolerance considerations. Based on this author's work experience, some of the most common mistakes of those performing cost studies during the conceptual design phase are directly correlated to their inability to recognize the installation tolerance reciprocal interdependencies of the processes being estimated. For example, the emphasis is placed on the touch labor hours to process a hole and the remaining considerations are either not discretely considered or buried in a CER. It is possible that one hole may seem relatively simple from the perspective of "direct labor hours to drill," but can lead to a subsequent requirement for a design tool – then possibly a design tool to make the design tool -- and so on. The failure to identify and schedule tooling requirements typically has far greater impact on total cost than the per-hole CER value or the hole quantity allocated by the estimator. In the next section, capability is discussed in the context of resources (management strategy.)

7.5.2 Hole Processing Systems Capability – Context 2: Resources (Management Strategy)

A second aspect of hole processing capability is based on resources and the associated management strategy. Resources include direct labor hours, machine hours, and procured capability (i.e., dollars) associated with Fabrication and Assembly activities, (i.e., IDEF0 diagrams, Chapter 2.) With regard to in-house processing, it is highly unlikely all hole processing systems are physically located in one location in "Detail Fabrication." (Note: Detail Fabrication is defined in Figure lower-level CBS in Figure 7.3, page 180.) Quite often, highly specialized hole processing equipment is located in specific work areas, and a variety of designs are routed to these areas. Similarly, fabrication organizations may have some hole processing capability dedicated based on the type of work being performed, i.e., NC machining, composites, tubing systems, etc. The way in which hole processing systems, and the personnel that utilize them, are assigned is based management's strategy for utilizing the hole processing capability. The current management strategy for hole processing systems and other fabrication processing systems is conveyed via the CBS lower-level information hierarchies (i.e., Figure 7.4, page 181).

The statements above provide insights into the reciprocal interdependencies related to the "resources" reciprocal interdependencies associated with hole processing capability. Recall the RIM-Diagram in Table 7.1 on page 175. This is an example of the lower-level detail for the "Resources" reciprocal interdependencies shown in the first column of this RIM-diagram. In the next section, capability is discussed in the context of sequencing (availability/scheduling.)

7.5.3 Hole Processing Systems Capability – Context 3: Sequencing (Availability/Scheduling)

The third context of hole processing systems capability is based on the sequencing (availability/scheduling) of hole processing systems. In order to consider sequencing availability, multiple reciprocal interdependences are addressed concurrently. Once a design requirement for a particular hole (i.e., hole-related design feature) is established on a new design - in order to use the in-house capability - the availability of the appropriate hole processing system must be determined based on capacity within a stipulated (scheduled) timeframe of need. Recall the RIM-Diagram in Table 7.1 on page 175. This context of capability is an example of lower-level detail for the "Sequence" reciprocal interdependencies shown in the first column of this diagram.

Now that "capability" has been discussed in three contexts [e.g., technical, resources, and sequencing] it can be illustrated in lower-level RIM-diagram. In the next section, a RIM-diagram for "capability" is illustrated and discussed.

7.6 RIM-Diagram for Manufacturing Capabilities-Based Decision Making

A RIM-Diagram incorporating the previously discussed contexts of capability is presented in Table 7.2. A discussion of Table 7.2 follows the RIM-diagram.

Table 7.2 RIM-Diagram of Manufacturing Capabilities

Manufacturing Capabilities	**COMMON** **Available** **But Not Well Organized** **(Information Silos)**	**COMMON** **Not Available or Poorly Estimated**	**NEW**
TECHNICAL Factory Management, Planning, Tooling, & Fabrication Processes *Items in blue italics are relatively easy to resolve; Others take more work*	*Arrow indications a subset or different level of the first column* *CBS work center information* *M&P specifications (CBS)* *Equipment inventory and specifications (CBS)* *Manufacturing engineering studies and preferences (CBS)* Manufacturing preferences (CBS and **features**) Assembly tolerance relationships Process-to-process relationships Tool manufacturing work centers (not discussed in this research)	*Work center information linked to **processing information*** **Design features** based on selective anticipation	Identify requirements: Part features -------------------- Similar for external suppliers
Tools Design specific Non-design specific	Design tools - tool classification and control system *Non-design tools (by CBS)*	**Design features** Tool classification and control system (by **tool codes** by **design feature**- and by CBS where used **Tool design features**	Identify requirements: Part features Tool features -------------------- Similar for external suppliers
RESOURCES Business Management Labor/Personnel ***(Paid a great deal of attention in the literature)***	CBS hierarchy to the work center level defines where the process is available (baseline assumption) WBS defines where procured items are needed Touch labor -parametric, CERs, labor standards, other direct labor factors	Touch labor estimating tools sensitive to both **features** and **sequencing** issues **Other direct labor task based** estimating approaches/logic	Identify sources -------------------- Quotes based on: Process Features
Procurement dollars	Relationships based on historical information	Estimating tools that are **design based for purchased items**	-------------------- Quotes
Factory Management Labor/Personnel	CBS hierarchy Planning logic Work measurement system Historical data in MES	**Features** and processes explanations **Feature-based** linkages to other activities Manufacturing preferences based on design **features**	
Procurement dollars	Based on orders	Relationships of orders to design	
SEQUENCING Business Management Master Schedule	Master Schedule and high-level internal schedules (SWBS)	Relationships based on selective anticipation features by CBS	Both internal and external: Clearly defined links to the Master Schedule (SWBS) and CBSdesignations used by and the MES
Factory Management Availability (Capacity)	MES generated schedules and capacity relationships	Clearly defined links between the SWBS, CBS, and MES	

The RIM-diagramming strategy for illustrating the management of reciprocal interdependencies related to “capability” is slightly different from the RIM-diagramming procedure presented earlier for “project management” in Table 7.1, page 175. The three major reciprocal interdependency levels are the same as the first RIM-Diagram in Table 7.1, i.e., “Technical, Resources, and Sequence.” Now, in Table 7.2, additional levels have been added to “Resources” and are designated as “Labor/Personnel” and “Procurement dollars”, (i.e., material, tooling, etc.) Under “Technical,” the “Process and Tools” section of Table 7.1 is now broken down into two, separate levels in Table 7.2, “Processes” and “Tools.” Further, “Tools” in Table 7.2 is further subdivided into two levels: “Design specific” and “Non-design specific.”

The “Commonality” column of Table 7.1 has now been expanded into two “Common” columns in Table 7.2. This two-column approach is used to conceptualize how common information can be converted to common knowledge within the enterprise. The last column on both diagrams is still labeled as “New.” Less attention is paid to “New” aspects of reciprocal interdependencies in RIM-diagramming efforts because the focus is on known/common information related to in-house processes.

The first “Common” column identifies where information is available, but it is typically not structured or organized in a manner making it easily accessible to the envisioned user of the DSS - the IPT member. In addition, this column provides some significant baseline assumptions and where information silos are identified. The problems caused by information silos can be alleviated by interfacing the DSS with other enterprise systems in a context useful to IPT members for their particular decision making needs. For example, the enterprise typically expends a great deal of resources developing “material and process (M&P) specifications, equipment specifications, and manufacturing engineering studies. However, in order for the information to be useful to IPTs, it requires organization in a manner relatable to specific CBS work centers used in routing logic and work instructions.

The second “Common” column identifies where additional work is required to define the information and the sources of information. For example, “Part features” and a methodology for their utilization utilizing “selective anticipation” requires definition. In addition, new requirements for “Tools” information queries are identified, such as “by tool codes by part feature.” Lastly, a requirement to further categorize the definition of features using selective anticipation is identified.

The last column is in Table 7.2 titled, “New.” This column is used as a placeholder for the identification requirements and sources of information for processes not currently defined in-house.

A technical system addition appears in the second column of the RIM-diagram, i.e., “tool classification and control system.” A general discussion of the system is offered. Tool designs are the responsibility of the Tool Design activity (i.e., IDEF0 diagram Activity 6, Figure 2.6, page 55). Tool designs are typically classified and controlled using tool codes (i.e., tool nomenclature/names) and tool numbers in a manner similar to how detail designs are classified and controlled using design nomenclature and unique numbers. (Additional discussion of tool codes is available in Appendix B.) Examples of tool codes are holding fixture, drill plate, assembly fixture, etc. In addition, some enterprises classify electronic information, such as NC tapes, as a design tool and assign a code (e.g., milling tape).

In this research, it is assumed that a tool classification and control system exists. Further it is assumed that changes are likely required in the tool classification and control system – specifically the additions of: 1) “Part features” information, 2) “Tool design features” information, and 3) the “CBS where the design tool is used.”

This type of information is assumed in the conceptual framework because if it does not exist, then the usefulness of a DSS for conceptual design decision making is greatly diminished. Based on this author’s work experience, when this type of tooling information is not formatted and organized for reuse, IPT members develop their own ad hoc approaches to collecting and utilizing historical information. In addition, recall from Chapter 1, Section 1.1.1.3, page 8, ad hoc approaches result when information sources are not linked in a manner that supports the needs of users. The information hierarchies related to the “tool classification and control system” are specifically discussed later in Section 7.8.

All of the items within Table 7.2 are not fully explained at this time, and the executive summary of RIM-diagramming efforts is offered. RIM-diagramming efforts in Table 7.2 result in two major products: 1) typical information silos converted to conceptual information hierarchies and 2) the higher-level organization of the reciprocal interdependencies management conceptual framework based on capability.

It is understood there are many ways to construct a conceptual framework for systematically defining the extremely large enterprise information “jigsaw puzzle” required for meeting the information needs of IPT decision making. The previously defined contexts/reciprocal interdependencies of capability are the organizing approach taken by this author.

The RIM-based conceptual framework should not be confused with conceptual information hierarchies. Conceptual information hierarchies are similar to databases – while the knowledge links represented by the conceptual framework are a two-dimensional organization illustration of a multidimensional knowledge construct. The conceptual framework's RIM capabilities "hierarchies" (i.e., Figure 7.6) are for keeping track of knowledge links development only – not the absolute layout of computer architecture.

Figure 7.5 illustrates the conversion of some elements within the "Common – Available But Not Well Organized (Information Silos)" column in Table 7.2 into conceptual information hierarchies. The information hierarchies are presented as a segment of conceptual work center information hierarchies. Some of the work center information has not been specifically discussed, but its relevance and usefulness are nearly self-explanatory. For example, the work center location, layout, and process descriptions, etc. information is potentially very beneficial for newer employers who may be unfamiliar with the manufacturing organization.

- CBS Work Center (WC) Data
  - WC number ◀
  - WC location
  - WC layout
  - WC Process descriptions
  - WC Worker classifications
  - WC Processing system information
    - WC most-used Material & Processes (M&P) specifications
    - WC Non-design tools inventory
    - WC Equipment inventory
      - Correlated to features (TBD)

CBS work center number is used in work instructions routing, the work measurement application approach, MES scheduling logic, MES capacity forecasting, manufacturing engineering studies, etc. The vision of the RIM-based DSS is that the work center is used to organize manufacturing knowledge.

Figure 7.5 Information Silos in Table 7.2 Correlated to Conceptual Information Hierarchies

In Figure 7.6, the conceptual framework's RIM capabilities "hierarchies" are offered. Again, this figure is for keeping track of conceptual framework information development and should not be confused with computer information systems hierarchies.

The section numbers in parentheses and color-coded in bold green indicate the section in Chapter 7 where the reciprocal interdependencies (knowledge links) are discussed. Items listed in black have already been discussed in previous sections of Chapter 7, and items listed in blue italics are yet to be explained. Notes in red indicate specific segments or topics that will not be addressed due to added complexity and time constraints. The three contexts of capability discussed using the example of hole processing systems are highlighted in yellow.

Again, this figure is a two-dimensional representation of multi-dimensional reciprocal interdependences (*knowledge links – technical, resources, sequencing, common, new, internal, and external*).

- *Design Processing Categories* **(Section 7.7)**
  - Product Data Management System (EBOM/Product Structure) **(Section 7.3; Section 7.8.2)**
    - *Features [Features*$_{\text{DesignSelectiveAnticipation (Mfg)}}$ *+ Features*$_{\text{ManufacturingSelectiveAnticipation (Design)}}$*]* **(Section 7.8.1)** **(Section 7.9.2)**
      - *Feedforward Planning Model (FFPM)*
        - CBS Work Centers **(Section 7.4.2)**
          - **#1** Technical processing systems information
            - Material and processes (M&P) standards and specifications by work center **(Section 7.6)**
            - *Equipment inventory* ***(Section 7.8)***
              - *Equip specs correlated to Features*$_{\text{DesignSelectiveAnticipation (Mfg)}}$ *+ Features*$_{\text{ManufacturingSelectiveAnticipation (Design)}}$ *+ Features*$_{\text{DesignOther(Mfg)}}$
            - Manufacturing Engineering studies by work center **(Section 7.6)**
            - *Specific processing capabilities limits [Features*$_{\text{DesignSelectiveAnticipation(Mfg)}}$ *Features*$_{\text{ManufacturingSelectiveAnticipation(Design)}}$*]* **(Section 7.9)**
            - *Design specific tooling used on past designs (historical data by product by type, i.e., part of tool classification and control system)* **(Section 7.8.2)**
              - *Tool codes (Tool Type; Features*$_{\text{DesignSelective anticipation (Mfg)}}$ *)*
              - *Tools to make tools on past designs*
                - Tool features (Will not be addressed)
            - Non-design specific tools (located in the areas, such as portable hole processing systems) inventory **(Section 7.6)**
          - **#2** *Resources (management strategy)* (overhead not discussed)
            - *Direct labor hours (touch)* **(Section 7.10)**
            - *Machine hours* **(Section 7.10)**
            - *Direct labor hours (other)* **(Section 7.10)**
            - *Procurement dollars* **(Section 7.10)**
          - **#3** *Sequencing (availability)*
            - *Sequence decisions based on the management of existing requirements (already planned for other products)* **(Section 7.11)**
              - *Labor hours by shift by timeframe* **(Section 7.11)**
              - *Machine hours by shift by timeframe* **(Section 7.11)**
            - *Technical sequencing considerations linked with Master Schedule (internal scheduling* **(Section 7.12)**
            - *Sequencing decisions based on management of new requirements by work center (incomplete designs)* **(Section 7.13)**

Even a very low level of detail – such as hole processing reciprocal interdependencies – can be described within the three contexts of manufacturing capabilities reciprocal interdependencies i.e.,
1) *Technical,*
2) *Resources (management strategy), and*
3) *Sequencing (scheduling/ availability)*

Highlighted numbers refer to capability contexts discussed in Section 7.5 from the perspective of hole processing systems

Figure 7.6 RIM-Based DSS Development Framework Based on the RIM-diagram of Manufacturing Capabilities

The RIM-based DSS development framework specifically addresses the translation issues identified in RIM-diagramming efforts. The framework is the starting point for subsequent conceptual information hierarchies and data development. The framework in Figure 7.6 is not to be confused with an information hierarchy that directly correlates to a computer architecture. It is instead a means of keeping track with the development of strategies for improved reciprocal interdependencies management (RIM).

The RIM-based capability representation facilitates utilization of the envisioned DSS in the following manner:

1) The "Processing Category" is selected. (This is marked TBD and is presented in blue italics because this area of the DSS is yet to be defined.)

2) EBOM information is retrieved from a "Product Data Management" system. (This is marked TBD and is presented in blue italics because this area of the DSS has yet to be defined.)

3) "Features" which have been categorized as "Design Selective Anticipation" features and "Manufacturing Selective Anticipation" features have been used to establish a feedforward planning model. (This is marked TBD and is presented in blue italics because this area of the DSS has yet to be explained.)

4) The "Feedforward Planning Model" (FFPM) organizes CBS work center information for the IPT within the context of the "Processing Category." (This is marked TBD and is presented in blue italics because it requires the definition of all hierarchies below it to be defined for completion.)

5) Once a CBS work center is designated by the FFPM, CBS work center based information is organized and provided to the IPT for decision making.
    a. Processing systems information is information related to current equipment and facilities, as well as historical databases.
    b. Technical, resources, and sequencing information baselines are developed by the system as starting points and may require additional information input. (Areas marked in blue italics have not been defined.)

The "Feedforward Planning Model" (FFPM) is the mechanism/logic within the RIM-based facilitating the management of reciprocal interdependencies and anticipated "capability" (as defined in the three contexts from Section 7.5) at a level of detail required for effective conceptual design decision making. In order to develop the FFPM for the conceptual DSS, each segment in blue in Figure 7.6 must be systematically addressed. The remainder of Chapter 7 is devoted to this undertaking.

7.7 Design Processing Categories

In this section, the “Design Processing Categories” segment of Figure 7.6 is explained. As a starting point, lower-level process definitions are already defined in the DSS by default, i.e., they are defined within CBS work center charters/descriptions that correlate to Figure 7.4 on page 181. (Figure 7.4 - Lower-Level CBS Information Hierarchies for Detail Fabrication.) Other categories should be defined by a cross-functional effort between activities where these definitions are relatable to other enterprise systems.

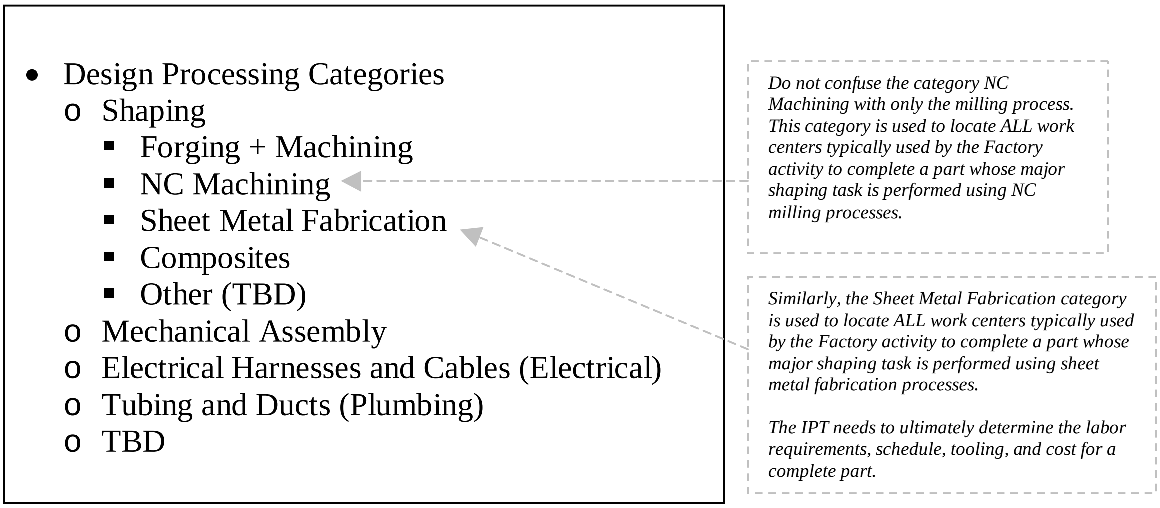
In the conceptual RIM-based DSS, the higher-level “NC machining processing category” is selected when NC machining is used to mill (e.g., shape) plate material, and it includes all other processes required to complete the detail design. It is interesting to note that none of the literature reviewed which utilized NC milling examples provided insights to the other processes involved in completing an NC machined detail design or their sequence of occurrence. Several articles provide a great deal of detail related to machining complex designs, and then jump to an estimate of total cost for a design. The reader is left to speculate how (or even whether) the other processes are considered, how tooling decisions are made, what assembly tolerance information is considered, and how the time/schedule element of cost calculation is applied. Similarly, the literature rarely explains the source of the schedule duration that is used to develop cost estimates. The reader is also often left to make assumptions as to how the cost is developed and used based solely on complex formulas and diagrams, and it is difficult to make the connection to real world IPT decision making. Based on working-level IPT responsibilities discussed in Chapter 5, Section 5.1 and this author’s work experience, IPT members typically need more insights to the details behind a cost estimate than these approaches have to offer. Cost estimates alone are not sufficient to build an integrated master plan and master schedule or effectively manage IPT-level tasks.

There are many ways to envision how a DSS would be used by an IPT. In simplest terms, this research assumes that a conceptual representation of a design is being considered, and the IPT members need information related to the manufacture of the design using “NC Machining” as defined earlier. The IPT enters the required information and an assortment of feedback related to in-house process capabilities is made available to the IPT based on the entries.

The RIM-based DSS is not intended to define the lower-level topology of an NC machined surface. Instead, the RIM-based DSS queries the enterprise systems to find the best match of historical data related to the design task at hand. The RIM-based DSS provides the process capabilities by work center as well as examples of manufacturing engineering studies to “show” the engineer what topologies have been successful in the past, as well as configurations that have caused problems. The RIM-based DSS gives the IPT the best starting point possible, considering there is very little detail actually available during conceptual design.

If an IPT member wishes to compare “NC Machining” to “Composites Fabrication,” then two different reports are generated, and the user compares these reports for differences. This does not mean that the information hierarchies within the envisioned DSS could not be used to develop an enhancement to directly compare material types (e.g. aluminum versus composite) for a specific detail design. Once RIM approaches are used to define “Composites Fabrication,” then this type of comparative procedure is possible. However, the amount of RIM-diagramming associated with development of the conceptual information hierarchies make the tasks infeasible for this research due to time constraints.

The conceptual information hierarchies for “Design Processing Categories” are as follows:



- Design Processing Categories
  - Shaping
    - Forging + Machining
    - NC Machining
    - Sheet Metal Fabrication
    - Composites
    - Other (TBD)
  - Mechanical Assembly
  - Electrical Harnesses and Cables (Electrical)
  - Tubing and Ducts (Plumbing)
  - TBD

Do not confuse the category NC Machining with only the milling process. This category is used to locate ALL work centers typically used by the Factory activity to complete a part whose major shaping task is performed using NC milling processes.

Similarly, the Sheet Metal Fabrication category is used to locate ALL work centers typically used by the Factory activity to complete a part whose major shaping task is performed using sheet metal fabrication processes.

The IPT needs to ultimately determine the labor requirements, schedule, tooling, and cost for a complete part.

Figure 7.7 Information Hierarchies for Design Processing Categories

Note “Design Processing Categories” are visible in Figure 7.6, but the complete information hierarchy including “Shaping, Forging, NC Machining, etc.” is not visible in the figure. This is because the information in Figure 7.7 at lower-level, or different dimension, than Figure 7.6

The next section, the systematic definition of the conceptual framework illustrated in Figure 7.6 continues.

7.8 Product Data Management, Design Features, and the Tool Classification and Control System

In this section, segments of Figure 7.6 labeled “Product Data Management System,” “Features”, and “tool classification and control system” are discussed. First, a high-level discussion of design features is offered and specific design selective anticipation features for NC machining are identified. Next, the basic contents of the PDMS are presented. This is followed by a discussion of the tool classification and control system hierarchies, and finally, Figure 7.6 is updated to reflect the knowledge links developed in this section.

Developing a strategy to manage the reciprocal interdependencies involving design features is one of the more difficult aspects of the RIM-based DSS to define; in particular, the use of features in the context of selective anticipation. According to Verganti’s findings, selective anticipation is the most difficult exercise of feedforward planning. Selective anticipation involves anticipating only the right amount of detail required to verify coherence, while at the same time correlating the design detail in the appropriate contexts.

The reciprocal interdependencies involved with design features are far more multi-dimensional than any considered thus far and certain areas of the solution space can only be assumed at this point. In general terms, a “manufacturing feature” is a subset of "design features" that conveys information to manufacturing regarding processing selections or assists in the reuse of enterprise data.

The solution space for design features is defined by the equation 7-1:

$$\begin{aligned}\Sigma\ \text{Features} = {} & \text{Features}_{\text{DesignSelectiveAnticipation(Mfg)}} + \text{Features}_{\text{ManufacturingSelectiveAnticipation(Design)}} + \\ & \text{Features}_{\text{DesignOther(Mfg)}} + \\ & \Sigma[\text{Features}_{\text{DesignSelectiveAnticpation(x)}} + \text{Features}_{\text{(x)SelectiveAnticipation(Design)}} + \\ & \text{Features}_{\text{DesignOther(x)}}] \qquad (7\text{-}1)\end{aligned}$$

Where,

Σ Features = the total set of all possible features

$\text{Feature}_{\text{DesignSelectiveAnticipation(Mfg)}}$ = the set of features that must be first identified by design to begin to manage reciprocal interdependencies that exist between Design and Manufacturing using feedfoward planning.

$\text{Feature}_{\text{ManufacturingSelectiveAnticipation(Design)}}$ = the set of features identified by Manufacturing after $\text{Feature}_{\text{DesignSelectiveAnticipation(Mfg)}}$ are identified by design that serve as the starting point for reciprocal interdependencies management and feedforward planning.
$\text{Features}_{\text{DesignOther(Mfg)}}$ = the remaining features identified by Design as the design matures. The absence of this knowledge does not critically inhibit conceptual design decision making.

$\text{Features}_{\text{DesignSelectiveAnticipation(x)}}$ = the set of features that must be first identified by Design to begin to manage reciprocal interdependencies that exist between Design and an unidentified entity, x, using feedfoward planning.

$\text{Features}_{\text{(x)SelectiveAnticipation(Design)}}$ = the set of features that are identified by entity, x after $\text{Feature}_{\text{DesignSelective Anticipation(x)}}$ are identified by Design which serve as the starting point for reciprocal interdependencies management and feedforward planning.

$\text{Features}_{\text{DesignOther(x)}}$ = the remaining features identified by Design as the design matures. The absence of this knowledge does not critically inhibit conceptual design decision making.

Based on this broad definition of features, the next step of DSS development involves identifying "selective anticipation features."

7.8.1 Design Selective Anticipation Features for Detail Fabrication

"Design selective anticipation features" [i.e., Figure 7.6 – $Features_{DesignSelectiveAnticipation\ (Mfg)}$] are those features that are known, or can be reasonably estimated, early in the conceptual design phase. Since the product is an aircraft, and aircraft have been manufactured before, then the design process is not totally new. Similarly, certain "features" of an aircraft can be defined in broad terms that have commonality to past designs. Design selective anticipation features are important data entries/inputs for the Feedforward Planning Model.

Even though it is not possible to define/specify the complete list of features at this point, it is assumed there is some number of features in the solution space and the design selective anticipation features are a subset of the total.

The types of engineering data available during early conceptual design will likely differ depending upon the product being developed. Since the specific case in this research is aircraft manufacturing, it is necessary to identify the features information typically available during conceptual design that have a quantifiable impact on manufacturing tasks. The following listing of conceptual design features information is based on combining material from three sources, Chapman (2004), Hall (2000), and Morrison and Neff (1997). This list is *not* intended to serve as the complete list of conceptual design data available and is oriented more toward structure.

- Inboard profile [Consists of at least a side-view cross section and, depending on the complexity of the aircraft, top-view and front-view cross sections. It is used to allocate space among various systems. It assists in the identification and location of the propulsion system and fuel, avionics, crew station, payload, and the primary structure such as bulkheads. Provides an initial concept of overall size and shape, and serves other design functions such as outer mold line (OML), center of gravity, water line, fuselage station, and butt line.]

- Preliminary estimates of understructure arrangement

- Preliminary estimates of weight

- Preliminary estimates of material types and proportions

In order to develop and use the FFPM, an assumption of “design selective anticipation features” must be made in order to narrow the solution space and provide a starting point for the consideration of multiple reciprocal interdependencies. The list of “design selective anticipation features” for the NC machining processing category is offered in Figure 7.8.

- Detail type
  - Material type
  - Finished weight (target)
  - Part envelope
    - Length (longest)
    - Width (next longest)
    - Depth (shortest)
  - Surface area (two dimensional-one side, or 2D-1S)
  - Service life {fracture critical}
  - Subassembly process

Figure 7.8 Design Selective Anticipation Features for the NC Machining Processing Category

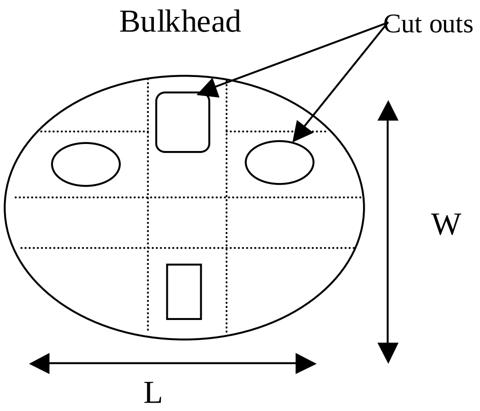
In Figure 7.8, “Detail type” is based on reference material presented in Appendix B and the product structure presented in Figure 7.1, page 175. “Detail type” examples are bulkhead, frame, floor, web, support, etc. Nomenclature (part naming) has meaning within the context of design, and is used to help the designer to manage design reciprocal interdependencies related to function.

“Material type” is self-explanatory. Based on reference material presented in Appendix B, the most common materials used in the aircraft industry are aluminum, titanium, steel, and composites. Within the RIM-based DSS defined, the “NC Machining Process” category does not have capability for a “composite” material type, so if this material is selected as an input, the DSS provides appropriate feedback.

“Finished weight,” or an estimated target, is self-explanatory. Weight estimates are used for aircraft sizing.

“Part envelope” is derived from OML definition and is used in aircraft sizing. It is easy to conceptualize how this information provides insights into material handling, work surfaces requirements, and equipment bed surfaces, such as milling machines, tape laying machines, specialty drilling machines, etc. A work measurement engineer can use these categories to restructure the work measurement data to be sensitive only to these features available during conceptual design. Similarly, if machine and equipment information within a work center is cataloged/organized by the same types of measurements, then automated comparisons are possible.

The “Part envelope” depth is the primary direction in which work will be accomplished, such as the direction the cutter faces during processing, or the orientation of the design as it rests on a surface or work bench. Figure 7.9 provides an illustration of "Part envelope" definition.



Depth cannot be seen in this view.

Length (L) and width (W) are based on envisioning how the plate would rest on the milling machine bed. A best guess is close enough. The designer can use the capability information in the DSS to get an understanding of the context of what machine bed means.

Once selective anticipation features are used in the DSS, it will provide feedback by work center on equipment.

Note: Figure is not meant to be representative of all possible bulkhead configurations. On some types of aircraft, a "bulkhead assembly" may be composed of machined details.

Figure 7.9 Part Envelope Definition of an Aircraft Bulkhead

The "part envelope" definition is an example where the Engineering activity incorporates information into the PDMS that have specific usefulness to downstream users. This definition is not for Engineering per se, it is defined to help the Factory Management, Planning, and Tool design activities efficiently locate information within their systems to assist the IPT (including the designer) in decision making. If the engineering activity incorporates the details other activities use during the detail design phase, then enterprise systems can communicate.

The RIM-based DSS provides IPT members with definitions and explanations of "Part envelope" (or other technical terminologies) at the "Design Processing Categories" level. It is particular important that a DSS provides conceptual representations of unusual envelopes to help the user make the best estimate possible.

The “Surface area” (i.e., two-dimensional, one-side surface, or 2D-1S) is represented in Figure 6.9. This surface area definition does not include the surface area of any internal characteristics that cannot be seen in the two-dimensional view in Figure 6.9. The outer mold line (OML) information is used as the reference to make a best estimate of 2D-1S surface area as illustrated in Figure 7.9. Even if the design is not a bulkhead, the OML and the fuselage station locations from sizing efforts can also be used to estimate similar surface areas for longitudinal structural members. Again, the envisioned DSS provides IPT members with explanations of these types of definitions at the “Design Processing Categories” level in order to avoid application errors.

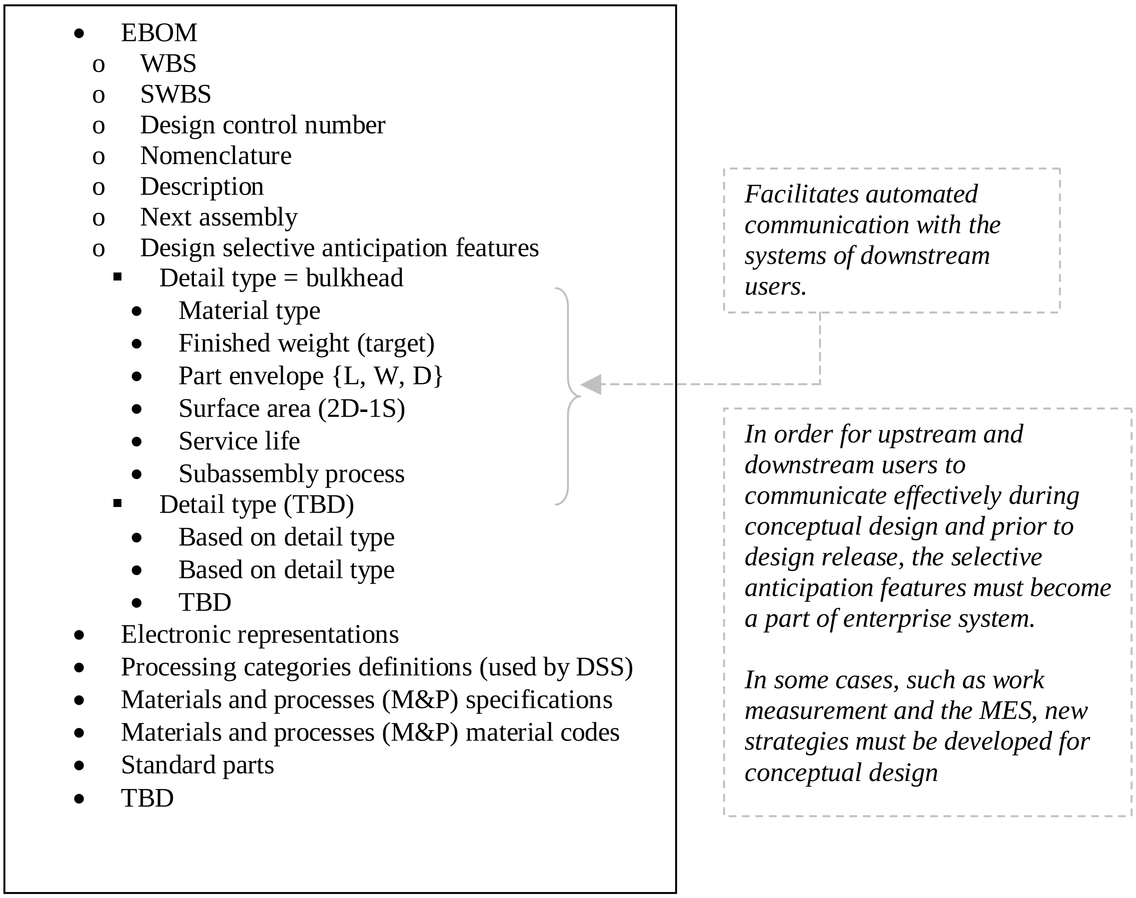
Even though this research does not specifically model “Service life,” the importance of service life is understood, and a placeholder is provided in Figure 7.9. The reason “fracture critical” is enclosed within brackets is to highlight that the baseline service life assumption for a bulkhead is being stipulated as “fracture critical.” For the initial purposes of the conceptual DSS, the sensitivity is “fracture critical” as a safety of flight structure as described in Appendix B. A service life example in Appendix B uses fracture critical 1, fracture critical 2, durability critical, and normal controls as four basic service life categories. However, it is understood that the modeling of service life ultimately likely requires a separate module/approach not covered in this research.

The use of the term “fracture critical” in the context of manufacturing processes conveys the necessity to take extra care in monitoring the job. Examples include increased occurrences of marking and inspection. If a design is not “fracture critical,” then the additional care is not required.

In Figure 7.8, “Subassembly process” conveys information with regard to whether a design is likely to be mechanically fastened, welded, etc. in the installation phase. Looking ahead to how a design is assembled to other structure (i.e., Assembly activity, IDEF0 diagram Activity 8, Figure 2.7, page 56) offers insights into detail fabrication decisions (i.e., Fabrication activity, IDEF0 diagram Activity 7, Figure 2.7, page 56)

7.8.2 Product Data Management System Hierarchies

For this research, it is assumed that a product data management system (PDMS) exists. A PDMS contains a configuration control numbering system, the product structure in Figure 7.1, design features discussed in Section 7.8.1, electronic representations, the WBS number scheme, and Schedule Work Breakdown Structure (SWBS) information. Conceptual PDMS information hierarchies are presented in Figure 7.10



- EBOM
    - WBS
    - SWBS
    - Design control number
    - Nomenclature
    - Description
    - Next assembly
    - Design selective anticipation features
        - Detail type = bulkhead
            - Material type
            - Finished weight (target)
            - Part envelope {L, W, D}
            - Surface area (2D-1S)
            - Service life
            - Subassembly process
        - Detail type (TBD)
            - Based on detail type
            - Based on detail type
            - TBD
- Electronic representations
- Processing categories definitions (used by DSS)
- Materials and processes (M&P) specifications
- Materials and processes (M&P) material codes
- Standard parts
- TBD

Facilitates automated communication with the systems of downstream users.

In order for upstream and downstream users to communicate effectively during conceptual design and prior to design release, the selective anticipation features must become a part of enterprise system.

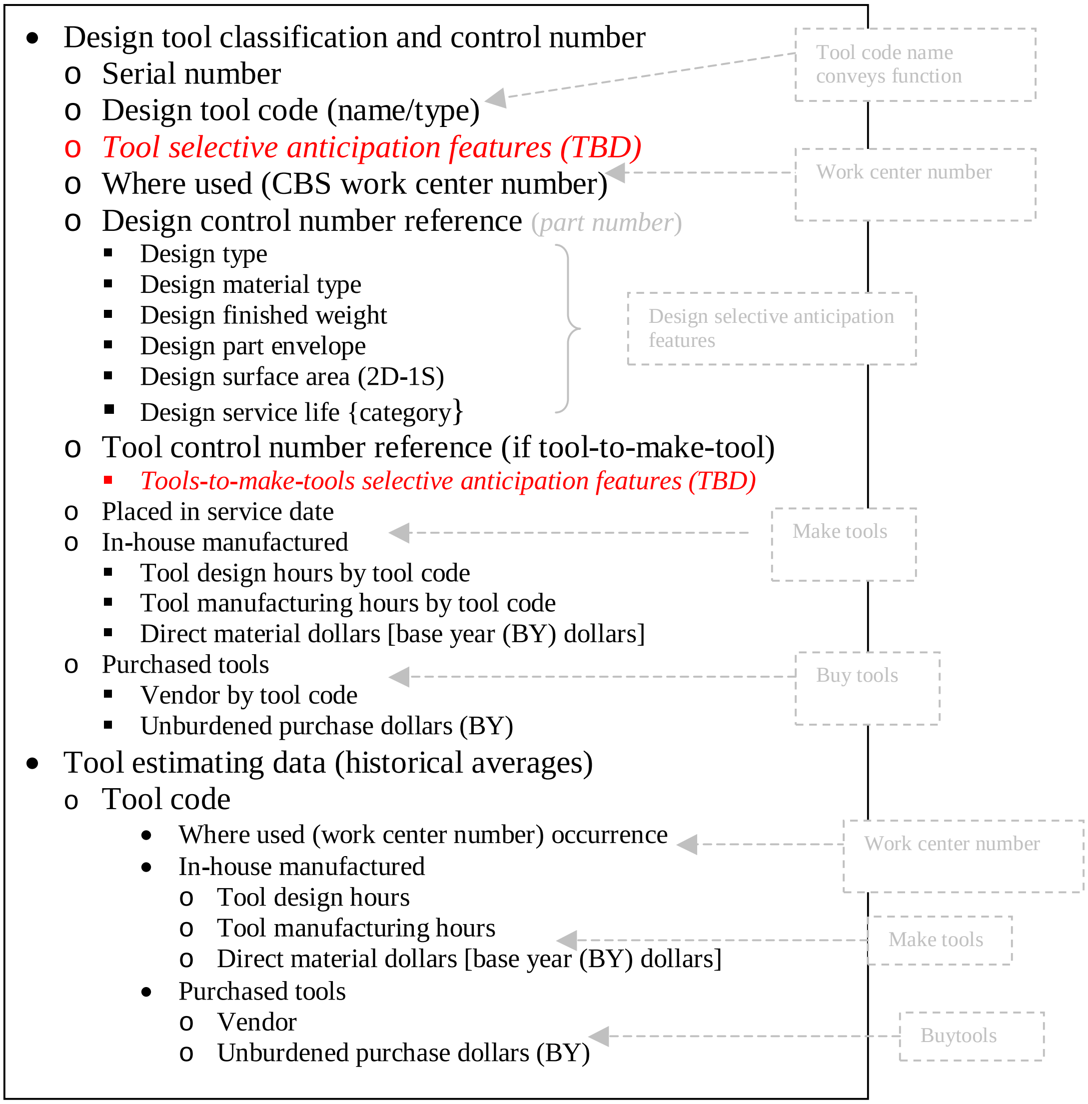
In some cases, such as work measurement and the MES, new strategies must be developed for conceptual design

Figure 7.10 PDMS Conceptual Information Hierarchies

The contents of the PDMS conceptual information hierarchies are essentially self-explanatory based on previous discussions of terminologies used or are discussed in Appendix B.

7.8.3 Tool Classification and Control System Hierarchies

Recall the “Technical processing systems information” segment in Figure 7.6, page 199. There is a segment dealing with historical data and the “tool classification and control system.” Since the “design selective anticipation features” have been defined in Figure 7.8, page 207, the information for storage and retrieval of information in the tool classification and control system is established based on these features reciprocal interdependencies. The conceptual tool classification and control system hierarchies are listed in Figure 7.11.



- Design tool classification and control number
  - Serial number
  - Design tool code (name/type)
  - *Tool selective anticipation features (TBD)*
  - Where used (CBS work center number)
  - Design control number reference *(part number)*
    - Design type
    - Design material type
    - Design finished weight
    - Design part envelope
    - Design surface area (2D-1S)
    - Design service life {category}
  - Tool control number reference (if tool-to-make-tool)
    - *Tools-to-make-tools selective anticipation features (TBD)*
  - Placed in service date
  - In-house manufactured
    - Tool design hours by tool code
    - Tool manufacturing hours by tool code
    - Direct material dollars [base year (BY) dollars]
  - Purchased tools
    - Vendor by tool code
    - Unburdened purchase dollars (BY)
- Tool estimating data (historical averages)
  - Tool code
    - Where used (work center number) occurrence
    - In-house manufactured
      - Tool design hours
      - Tool manufacturing hours
      - Direct material dollars [base year (BY) dollars]
    - Purchased tools
      - Vendor
      - Unburdened purchase dollars (BY)

Figure 7.11 Tool Classification and Control System Information Hierarchies

The design selective anticipation features link the design knowledge and the tooling knowledge. Because the design type is a bulkhead, the IPT is enabled to review only the tooling information related to bulkheads, and if desired, only those that are similar in size and weight to the design being considered.

The tool code is correlated to the work center where it is used (via the work center number) so this information can in turn be linked to a fabrication plan/routing sequence. Once the information related to tool codes is linked to the work center and the design type, then the tool family (groups of tools typically used to make a design) is much easier for the IPT to interpret.

Historical averages related to tool codes are available to everyone in the enterprise, as opposed to only those individuals who can write an ad hoc programs to retrieve the information.

The tool classification and control system contains information required to manage the reciprocal interdependencies between Engineering design information (i.e. IDEF0 Activity 3, Figure 2.5) and Tool Design information (i.e., IDEF0 Activity 6, Figure 2.6). The contents of the tool classification and control hierarchies in Figure 7.11 are explained as follows:

- “Tool classification and control number” is a unique number assigned to a specific tool for a specific job.
- “Serial number” is used to distinguish between rate tools for the same job.
- “Tool code” (name/type) conveys the basic function of a tool, examples include holding fixture, drill plate, etc.
- “Where used” conveys the work center in which a design tool is required. The work center information links tool utilization with work instructions routing for the detail design requiring the tool.

- “Design control reference number” is the same as the design number in the EBOM, and provides a link to the PDMS. Note that this type of field is populated when a tool is actually built. For the most part, the IPT is interested in the information at the bottom of the figure related to estimating the most likely tooling task for the new design based on historical data.

- “Design selective anticipation features” (e.g. as explained in Section 7.8.1) are integrated in the tool classification and control system, i.e., part type, part material type, etc. This information is *not* typically stored in tool design systems, but is required for electronically linking detail design knowledge and tool design knowledge, as well as enhanced simulation capabilities.

- “Tool control reference number” is required if the tool is used to make another tool.

- “Tools-to-make-tools selective anticipation features” are yet to be determined, but are required for the envisioned DSS and enhanced simulation capabilities. This segment of RIM-based DSS will not be discussed in this research for reasons previously discussed.

- “Placed in service dates” are used for design tooling maintenance decisions.

- “In-house manufactured” contains the information related to design tool manufacturing for specific design tools. This area of the information hierarchy correlates information from Tool Design (i.e., IDEF0 Activity 6) and Fabrication (i.e., IDEF0 Activity 7). Direct costs in dollars are recorded with a base year (BY) designation.

- “Purchased tools” contains the high-level purchasing information, i.e., the vendor name and the unburdened purchase cost in base year dollars for a specific tool.

- “Estimating data (historical averages)” contains standardized templates used for decision making in the absence of detailed tool design information.

- “TBD” is a placeholder signifying that other required elements of the tool classification and control system are likely to be discovered once more detailed work and RIM-diagramming are performed in the context of tool manufacturing processing.

The Feedforward Planning Model (FFPM) organizes information for a detail design by work center, so “Where used” is a key component of the tool classification and control system. Once work centers for processing a particular design type are identified, the tool code requirements by work center are estimated using historical occurrence information in the tool classification system.

Even though detail design processing patterns are given a great deal of consideration in the literature, based on this author's work experience, the estimation of design tooling requirements is more difficult. Most articles do not directly address tooling requirements (i.e., IDEF0 Activities 6 and 7), and tooling knowledge is oftentimes buried in a factor or an equation. In addition, the devastating effect on schedule performance that occurs when there is a failure to identify tooling requirements early on is not adequately addressed in the literature.

One detail design typically requires several tools for its fabrication. If one considers that various tooling scenarios that exist, i.e., tools-to-make-tools, then it quickly becomes apparent from the perspective of scheduling (and resource leveling) how important that these relationships are to the estimation of the design release date that supports the IPT's total project plan. Tool design selective anticipation features and associated processing relationships are not discussed in this research and are a part of planned future work.

7.8.4 Update of the DSS Information Hierarchy

Recall Figure 7.6, page 199, where the yet to be defined items are in blue italics. Figure 7.6 is now updated to create a new figure, Figure 7.12, to highlight the areas of the FFPM still requiring definition. Certain segments of "Technical processing systems information" are now complete and are color coded in black. The remaining segments requiring definition are offered in blue italics and the upcoming sections where these segments are discussed are colored in bolded green.

- *Design Processing Categories* **(Section 7.7)**
  - Product Data Management System (EBOM/Product Structure) **(Section 7.3; 7.8.2)**
    - *Features* [Features$_{\text{DesignSelectiveAnticipation (Mfg)}}$ *+ Features*$_{\textit{ManufacturingSelectiveAnticipation (Design)}}$*]* **(Section 7.8.1; Figure 7.8)** **(Section 7.9.2)**
- *Feedforward Planning Model (FFPM)*
  - CBS Work Centers **(Section 7.4.2)**
    - **#1** Technical processing systems information
      - M&P standards and specifications by work center **(Section 7.6)**
      - Equipment inventory **(Section 7.8)**
        - Equip specifications correlated to Features$_{\text{DesignSelectiveAnticipation (Mfg)}}$ + Features$_{\text{ManufacturingSelectiveAnticipation (Design)}}$ + Features$_{\text{DesignOther(Mfg)}}$
      - Manufacturing Engineering studies by work center **(Section 7.6)**
      - *Specific processing capabilities limits [Features*$_{\textit{DesignSelectiveAnticipation(Mfg)}}$ *Features*$_{\textit{ManufacturingSelectiveAnticipation(Design)}}$*]* **(Section 7.9)**
      - Design specific tooling used on past designs (historical data by product by type, i.e., part of tool classification and control system) **(Section 7.8.2)**
        - Tool codes (Tool Type; Features$_{\text{DesignSelective anticipation (Mfg)}}$)
        - Tools to make tools on past designs
          - Tool features (Will not be addressed)
      - Non-design specific tools (located in the areas, such as portable hole processing systems) inventory **(Section 7.6)**
    - **#2** *Resources (management strategy)* (overhead not discussed)
      - *Direct labor hours (touch)* **(Section 7.10)**
      - *Machine hours* **(Section 7.10)**
      - *Direct labor hours (other)* **(Section 7.10)**
      - *Procurement dollars* **(Section 7.10)**
    - **#3** *Sequencing (availability)*
      - *Sequence decisions based on the management of existing requirements (already planned for other products)* **(Section 7.11)**
        - *Labor hours by shift by timeframe* **(Section 7.11)**
        - *Machine hours by shift by timeframe* **(Section 7.11)**
      - *Technical sequencing considerations linked with Master Schedule (internal scheduling* **(Section 7.12)**
      - *Sequencing decisions based on management of new requirements by work center (incomplete designs)* **(Section 7.13)**

Highlighted numbers refer to capability contexts discussed in Section 7.5.

Figure 7.12 RIM Development Conceptual Framework (Update of Figure 7.6)

In the next section, the definition of Figure 7.12 continues.

7.9 Technical Processing Systems Information – Specific Processing Capabilities Limits (Based on Features)

In this section, the development of “Technical processing systems information” related to the segment titled “Specific processing capabilities limits” in Figure 7.12 is discussed. First, some of the key findings and concepts from Verganti’s study are reviewed in the context of technical information development and utilization by IPTs. Next, RIM-diagramming is used to identify feedforward planning opportunities in the context of capabilities limits by feature and work center. Finally, the beginnings of a FFPM fabrication plan are presented.

7.9.1 Importance of Technical Information and Teaming

Verganti’s research involves studying and describing product development teams’ anticipation of manufacturing constraints and opportunities during concept generation and product planning phases. Findings from 12 case studies related to teaming and early design decision making in the automobile, helicopter, and white-goods (small appliances) industries provide the basis of assertions.

Verganti concludes selective anticipation is the most difficult aspect of feedforward planning because it requires individuals to utilize only a small, unique set of information to make a decision. Some teams effectively utilized selective anticipation in feedforward planning efforts, while others could/did not. Verganti reports one of the issues noted by teams whose performance was poor on feedforward planning was - *the technical information believed needed to make timely and informed decisions is not available at project start.* Based on this author’s work experience, many IPT members do not understand how to work with sketchy information, and become fixated on the *unavailable* information - as opposed to focusing on selectively anticipating how to utilize the *availabl*e information. These individuals believe a decision cannot be made without a complete design.

Verganti also notes efforts related to selectively anticipating detailed design information are fruitless if the design information is not maintained, transferred, and exploited during subsequent product development activities. Further, he asserts that effective feedforward planning requires both “learning from past experience” and “learning from development of a new solution.” Learning from development requires the efforts of development be appropriately documented. If IPTs effectively “start over” on each new endeavor and the enterprise operates under the assumption that various types of knowledge start out at zero percent (i.e., Chapter 4, Figure 4.1, page 103), then learning from development is not occurring.

Further, Verganti discovered that successful anticipation of manufacturing constraints and opportunities during the conceptual design phase was correlated to the development of “preplanning knowledge,” i.e., knowledge developed and maintained well in advance of the presently identified need. However, lacking in his study are specific examples and explanation. Based on this author’s work experience in an IPT environment, Verganti’s assertion is valid; but extrapolation and elaboration are required based to correlate the study to the working-level IPT job roles and responsibilities discussed in Chapter 5, (i.e., Section 5.2, page 116.)

With regard to the “Technical information” (i.e., context 1, Figure 7.12, page 217) aspects of preplanning knowledge from an aircraft manufacturing perspective, manufacturing engineering plays the lead role for Detail Fabrication (and Assembly) technical information. (Manufacturing engineering is referenced in IDEF0 diagram Activity 5, Figure 2.6, page 55.) However, in many instances, manufacturing engineering information is organized in a format that supports ongoing production activities, but not the information needs of IPTs. This assertion is based on: 1) Verganti's findings, (e.g., most teams reported not having the information they needed), 2) problems noted in Chapter 1 dealing with the lack of success of concurrent engineering efforts, and 3) this author's practical work experience.

Manufacturing engineering is classically responsible for the following types of tasks:

- Performing studies of in-house process/equipment capabilities limits
- Managing the data associated with performance of studies related to process capabilities
- Identifying new equipment and integrating it with the existing facility
- Developing processing requirements for suppliers
- Performing benchmarking activities
- Developing the manufacturing plan (and associated tooling plan) for new products

However, the information resulting from manufacturing engineering efforts is typically not maintained in a format readily available for reuse by IPTs or integration with existing enterprise systems. (Arai et al., 2004; Prasad; 2000; Brown et al. 1997.) During conceptual design, the user of technical processing capabilities limits information must often develop RIM-relationships, i.e., make an ad hoc assessment as to the correlation of technical knowledge, resource knowledge, and sequencing knowledge related to required decision making.

Further, the literature review contains many articles that discuss “process capabilities limits” considerations for new designs as if these limits are novel or unknown - even though existing processes and equipment have been utilized on past designs (i.e., commonality as defined in Chapter 1).

In order to develop the envisioned DSS and realize its associated benefits, significant change is required with regard to how the enterprise obtains, formats, and maintains technical information that is typically related to manufacturing engineering efforts. The manufacturing engineering information is critical to success in “preplanning knowledge” and “learning by development.”

7.9.2 RIM-Diagramming of Technical Information: Specific Processing Capabilities Limits

Recall Figure 7.12, the “Technical” information piece contains a segment in blue italics titled “ Specific processing capabilities limits.” RIM-diagrams are offered in Tables 7.3 through 7.10 to explain the types of specific processing capabilities limits that are typically required by IPTs, but are unavailable. The information in the RIM-diagrams is attributed to manufacturing engineering (i.e., IDEF0 diagram Activity 5, Figure 2.6, page 55). In addition, the RIM-diagrams illustrate the type of computerized information queries conceptualized for the RIM-based DSS.

The previously identified “design selective anticipation features” (Figure 7.8, page 207) are inputs/entries made by the IPT to the DSS. Once the “design selective anticipation features" are entered, the "manufacturing selective anticipation features" are identified by the DSS. (This assumes that manufacturing engineering develops and maintains the appropriate data/information in information hierarchies that are relatable by the work center number.) The "manufacturing selective anticipation features" are not yet specified by the detail design, but in order to develop the preferred design, these features require consideration and planning as soon as possible.

Recall the design selective anticipation features from Figure 7.8. If the working-level IPT is considering a NC machined bulkhead detail design, which is later mechanically assembled/fastened, then the DSS input information is offered in Figure 7.13. (Variables are used in the figure as placeholders.)

IPT Selection Design Processing Category **= NC Machining**

- Detail Type **= Bulkhead**
  - Material Type **= n**
  - Finished Weight (target) **= w**
  - Part Envelope
    - Length (longest) = **L**
    - Width (next longest) = **W**
    - Depth (shortest) = **D**
  - Surface area (two dimensional-one side, or 2D-1S) = **SA**
  - Service Life {**= fracture critical**}
  - Subassembly process = **mechanical fastening**

Figure 7.13 Design Selective Anticipation Features for a Mechanically Fastened NC Machined Bulkhead (IPT Inputs in Blue Bold)

Once the DSS input information is established, the next step is to determine the pertinent reciprocal interdependences (i.e., knowledge links) existing between the "design selective anticipation features" and the "manufacturing selective anticipation features." The information in the RIM-diagrams in Tables 7.3 through 76.10 represents the

"Technical processing systems information" in Figure 7.12 that requires collection, electronic formatting, and maintenance in order for the DSS to provide feedback in the context of "Specific processing capabilities limits" to the IPT.

Before reviewing Tables 7.3 through 7.10 on the following pages, a cursory review of cost breakdown structure (CBS) work centers previously presented Figure 7.4, page 181, is recommended.   Figure 7.4 assists with correlating the work center information in the CBS to the tables presented. In addition, Tables 7.3 through 7.10 are not intended to discuss every possible technical processing relationship, but are offered for example purposes only.

Table 7.3 RIM-Diagram for NC Milling Group: 1 of 9

R I M T, R, S	**Manufacturing Capabilities by Work Center**	**COMMON Manufacturing Selective Anticipation Features**	**COMMON Technical Process Capabilities Limitations** ***(Ranges)***	**COMMON Technical Process Rules and Preferences** ***(Most desired within the range)***	**NEW (FUTURE)** **In-house planning** **---------------** **Vendor data**
		Expansion of related capabilities knowledge			
	3-Axis Milling *Note: Group numbers and work centers are from lower-level CBS, Figure 6.4*		After plate inspection and tooling holes ------------------------- Processing envelope correlated to part envelope Material handling equipment (features, part envelope, weight) Surface finish ranges	Machine bed Nominal = X	Plates can be surface milled before receipt ------------------- Identify vendors
Resource	5-Axis Milling	*Locating features associated with the IPT's manufacturing plan*	5-Axis is preferred resource to 5-Axis high speed based on management preference -------------------------		
Sequence			After surface milling (plate prep) --------------------------		
Technical			Processing envelope correlated to part envelope Material handling equipment (features, part envelope, weight) Surface finish ranges Hole processing Hole dia tol Hole loc tol Hole depth Web thickness (WT) Web thick tol Pocket size (PS) Stiffener thickness (ST) Stiffener thickness tolerance Cut outs Location tolerance Ratios Tables PS to WT Flange height to ST	In general, staying below the limits are preferable Exact values can be stated "Thinness" limit – consider chemical milling If limits require exceeding, then consider replanning for 5-Axis high speed work center Outside of limit, consult M.E.	Internal Test patterns and published results First-article test part required ------------------- External Vendor data Equipment Process coordination Turn key The same types of detailed technical information is coordinated with suppliers
	5-Axis High Speed	In general, same as 5-Axis Milling	In general, same as 5-Axis for sequencing and technical, but the specific values likely differ	In general, same as 5-Axis, but the values likely differ	In general, same as 5-Axis

"RIM" is listed in the far left column of Tables 7.3 through 7.10 to signify that "Technical, Resources, and Sequencing" reciprocal interdependencies are being considered concurrently. The "Work Center" column designates the Detail Fabrication work centers containing the touch labor resources, non-design tools, and design tooling utilized to manufacture aircraft NC machined bulkheads. (Refer to the prior explanation of CBS work centers correlating to Figure 7.4)

The next three columns are designated as "Common" because they deal with how past designs have been manufactured using in-house processes. The last column is identified as "New." This column specifies the general types of "preplanning knowledge" required for future decision making related to "new" products.

The first "Common" column deals with "Manufacturing Selective Anticipation Features." These are the features most critical to fabrication and/or installation sequencing in subassembly or component assembly. These features have not yet been discretely identified, but they are the features that should be in the forefront of IPT planning and decision making.

The identification of "manufacturing selective anticipation features" prior to actual design definition "feeds forward" manufacturing constraints and opportunities to an earlier point in the design process. In simple terms, manufacturing is conveying to engineering - *these are the most desirable features based on past experience and the constraints and opportunities associated with these features*. Instead of leaving each IPT member the task of identifying "manufacturing selective anticipation features," the DSS facilitates RIM by conveying "manufacturing selective anticipation features" identified and organized in a database by manufacturing engineering. The "manufacturing selective anticipation features" are the highest priority knowledge exchanges.

Note in Table 7.3 the work center "3-Axis milling" does not have any "manufacturing selective anticipation features" listed. The empty cell conveys there are limited technical implications to the rough milling that takes place prior to major milling. The IPTs cannot micromanage every work center, and it is necessary to prioritize the most significant "manufacturing selective anticipation features." As noted by Verganti, successful selective anticipation efforts result in narrowing the information considered, focusing efforts on the most critical decisions.

The second "Common" column is titled "Technical Process Capabilities Limitations." This column has a horizontal dashed line in it. The information above the dashed line deals with process sequencing with other Detail Fabrication work centers. The information below the dashed line deals with specific process values that can be relayed to the IPT and/or utilized by internal logic of the DSS. For example, the "Processing envelope" of the NC machining bed can be correlated to the "part envelope" (i.e., Figure 7.8, page 207) to provide instant feedback as to whether the detail design fits on the equipment in a work center. Similarly, material handling equipment availability can be considered using a combination of features, i.e., part envelope and weight. The surface finish capability limit ranges available in a particular work center can be conveyed to the IPT to guide decision making.

Other examples include specific machining limits for hole processing, milled web thickness, milled pockets sizes, etc. The "Technical Process Capability Limitations" column of the RIM-diagram organizes relevant ranges of numeric capability limits for each work center using manufacturing features. During early conceptual design, many of these features are not known, but the information is useful to provide design guidance as the design matures. For example, the exact configuration of machined pockets has not been defined in the two-dimensional, conceptual representation of the bulkhead illustrated in Figure 7.9, page 209, but pocket sizing limits information is useful to the designer/IPT as this aspect of the design is considered.

The third "Common" column in Tables 7.3 through 7.10 entitled "Technical Process Rules and Preferences." This column narrows the complete range of capability limits specified in the previous column to only a smaller subset of preferences, and it also provides general "rules of thumb" not stated in the previous "common" column.

For example, a machine may be capable of wide range of surface finishes, but the preferred finish is nominal, i.e., some yet to be determined value (x). Similarly, as a general rule, manufacturing prefers "looser" tolerances and to avoid "special processing" (e.g. chemical milling, forming, plating, or heat treatment). Special processing are processes that are not typically performed on all NC machined details. While preferences are worthy to consider, if a design requires more complex processing, then the defined limits in the previous "Technical Process Capabilities Limitations" suffices.

The last column in the tables, entitled "New," describes the information required to address new designs, and may contain a horizontal dashed line. The information above the horizontal dashed line pertains to decision making related to new processes or equipment utilized in-house. For example, when a new machine is purchased, it is expected that manufacturing engineering performs tests on various complex patterns and publishes the results of these tests electronically in a format accessible to outside users and the DSS. In addition, for a design type of “bulkhead,” the “New” column designates the manufacturing plan for a new 5-axis milling process includes a first-article test part.

The area below the horizontal dashed line in the “New” column pertains to vendor data in the context of new equipment purchases, supplier process coordination, and project coordination of “turnkey” jobs. In order to support early decision making, technical vendor data should be systematically developed, organized, and maintained.

If design requirements exceed the capabilities limitations of existing in-house processes, then effective decision making mandates the timely identification of new equipment/processes and/or the identification of outside suppliers to manufacture the design. If new equipment/process data and supplier data are not appropriately identified, then the decision making process related to “new” requirements is inefficient. If the manufacturing plan for a new product merely assumes “new requirements” can be achieved without appropriate validation procedures, then it results in what Verganti defines as “superficial anticipation.”

Now, the attention turns to the discussion of the “Manufacturing Selective Anticipation Features” identified by work center in Tables 7.3 through 7.10. Since an aircraft bulkhead is typically a first load item in an assembly sequence, the locating features that are machined into the bulkhead by the “5-Axis” work center (Table 7.3) are critical. (5-Axis is used instead of 5-Axis High Speed because the assumption is that the majority of requirements can be met using the less expensive machines.) If locating features are designed into the bulkhead, then it saves time in orienting subsequent structural parts in the assembly load sequence, and it also improves quality related to human error.

Similarly, the holes drilled in the “Specialty Hole Processing,” Table 7.4, have these types of subsequent structural parts orientation implications. Holes in bulkheads are typically used to:

- Pin-locate other structural detail designs
- Back-drill hole patterns in other structural designs
- Locate tools for drilling shared fastener patterns

Special processing requirements (Tables 7.7, 7.8, and 7.9) such as heat treatment, plating, and forming are typically “requirement” critical. A work center process is requirement critical when planning for tasks to be performed during fabrication and making appropriate schedule allowances are the most important considerations. Even if lower-level detail related to the specific special processing specifications cannot be identified, the IPT should consider the basic requirement early on; this deliberation has the potential to significantly improve schedule performance.

Similarly, identifying the requirement for electrical bonding, Table 7.6, is more important than knowing exactly how much bonding surface is required or the exact location on the design. The preference for performing electrical bonding is in Detail Fabrication, (i.e., IDEF0 diagram Activity 7, Figure 2.7, page 56) as opposed to Assembly (i.e., IDEF0 diagram Activity 8). When electrical bonding surface preparation tasks are performed in Assembly, it typically requires more labor hours or has greater impact on the critical path.

As mentioned earlier, Table 7.3 through 7.10 are not intended to discuss every possible technical processing systems relationship and are offered for example purposes only. These tables illustrate the types of technical processing information that require consistent coordination and dissemination throughout the enterprise, and in particular to the IPTs during conceptual design decision making.

Table 7.4 RIM-Diagram for Special Hole Processing Group: 2 of 9

R I M T, R, S	**Manufacturing Capabilities by Work Center**	**COMMON Manufacturing Selective Anticipation Features**	**COMMON Technical Process Capabilities Limitations**	**COMMON Technical Process Rules and Preferences**	**NEW (FUTURE)** In-house planning -------------- Vendor data
	Drilling/Boring type 1	**Resources** → **Sequencing** → *Hole processing type:* *Pinning hole* *Fastener pattern* **Technical** →	Process holes during NC milling first based on rule TBD ----------------------- After milling and cleaning Before heat treat --------------------- Processing envelope (PE) Material handling (MH) Hole process type Hole processing features: Hole dia tol Hole loc tol Hole depth	Looser tolerances preferred, but this may be a tooling plan critical process	---------------- Vendor data Equipment Process coordination Turn key
	Drilling/Boring type 2	Same as Type 1	Same as Type 1 but different values	Same as Type 1	Same as Type 1
	3-Axis (tooling holes)	*Most bulkheads are first load items and require some type of tooling holes*	Before plate milling After major milling Before heat treat ---------------------- PE MH Hole processing features Hole diameter tolerance (Hole dia tol) Hole location tolerance (Hole loc tol) Hole depth	Looser tolerances preferred, but this may be a tooling plan critical process	Requires coordination with tooling plan for assembly ---------------------- Vendor data Equipment Process coordination Turn key

Note: Group numbers and work centers are from lower-level CBS, Figure 7.4

Table 7.5 RIM-Diagram for Hand Finish Group: 3 of 9

RIM T, R, S	**Manufacturing Capabilities by Work Center**	**COMMON Manufacturing Selective Anticipation Features**	**COMMON Technical Process Capabilities Limitations**	**COMMON Technical Process Rules and Preferences**	**NEW (FUTURE)** In-house planning --------- Vendor data
	Vapor degrease		After major milling -------------------- PE & MH Limited technical significance	TBD	Not likely outsourced unless turnkey with milling
	Deburr		After vapor degrease -------------------- PE & MH Limited technical significance	TBD	Not likely outsourced unless turnkey with milling
	Tooling tab removal		After vapor degrease -------------------- PE & MH Limited technical significance	TBD	Not likely outsourced unless turnkey with milling
	Hole processing (portable systems)		After deburr and tab removal -------------------- PE & MH Limited technical significance Hole processing features: Hole dia tol Hole loc tol Hole depth	Looser tolerances Preferred Typically a rework area, as hole processing is planned for other work centers	Not likely outsourced unless turnkey with milling

Note: Group numbers and work centers are from lower-level CBS, Figure 7.4

Table 7.6 RIM-Diagram for Coatings Group: 4 of 9

RIM T, R, S	**Manufacturing Capabilities by Work Center**	**COMMON Manufacturing Selective Anticipation Features**	**COMMON Technical Process Capabilities Limitations**	**COMMON Technical Process Rules and Preferences**	**NEW (FUTURE)** In-house planning --------- Vendor data
	Wash/Clean		Before coatings ------------------------ PE & MH Requirement(Req) usually based on another process Limited technical significance	TBD	Not likely outsourced unless turnkey with detail completion
	Mask		After major milling Before painting ------------------------- PE & MH Limited technical significance Req based on painting and electrical bonding	TBD	Not likely outsourced unless turnkey with detail completion
	Prime		Before paint ------------------------- PE & MH Limited technical significance Req typically based on painting	TBD	Not likely outsourced unless turnkey with detail completion
	Paint	*Requirement*	After milling and specialty processing Process prior to inspection and stamping Limited technical significance ------------------------- PE & MH	During initial Detail Fabrication instead of returned later	Requires coordination with assembly plan ----------------- Vendor data Equipment Process coordination Turn key
	Electrical bonding	*Requirement*	After major milling After masking Before painting ------------------------- PE & MH Features: Bonded area Location tolerance	Looser tolerances Prefer templates Instead of tools During initial Detail Fabrication instead of returned later	Requires coordination with assembly plan ----------------- Vendor data Equipment Process coordination Turn key

Note: Group numbers and work centers are from lower-level CBS, Figure 7.4

Table 7.7 RIM-Diagram for Hardening and/or Special Treatment Group: 5 of 9

R I M T, R, S	**Manufacturing Capabilities by Work Center**	**COMMON Manufacturing Selective Anticipation Features**	**COMMON Technical Process Capabilities Limitations**	**COMMON Technical Process Rules and Preferences**	**NEW (FUTURE)** In-house planning ----------------- Vendor data
	Wash/Clean		Before special treatment ------------------- PE & MH Requirement usually based on another process Limited technical significance	TBD	Not likely outsourced as stand-alone item
	Heat treat	*Requirement*	Can be performed at various stages, but increases difficulty of other processes ------------------- PE & MH Process limits TBD	After major milling After hole processing After specialty processing During initial Detail Fabrication instead of returned later	Requires coordination with assembly plan ----------------- Vendor data Equipment Process coordination Turn key
	Heat treat age	*Requirement*	Similar to Heat treat ------------------- PE & MH Process features TBD	Similar to Heat treat	Similar to Heat treat

Note: Group numbers and work centers are from lower-level CBS, Figure 7.4

Table 7.8 RIM-Diagram for Chemical Processing Group: 6 of 9

R I M T, R, S	**Manufacturing Capabilities by Work Center**	**COMMON** **Manufacturing Selective Anticipation Features**	**COMMON** **Technical Process Capabilities Limitations**	**COMMON** **Technical Process Rules and Preferences**	**NEW (Future)** In-house planning ------------------- Vendor data
	Wash/Clean *Note: Group numbers and work centers are from lower-level CBS, Figure 7.4*		Before chemical processing ------------------------ PE & MH Requirement usually based on another process Limited technical significance	TBD	Not likely outsourced as a stand-alone process
	Annodize	*Requirement*	After milling Before hardening Can be performed at various stages, but increases difficulty of other processes -------------------------- PE & MH Process features: Area thickness Area thickness tol Area location tol	After major milling After hole processing After specialty processing During initial Detail Fabrication instead of returned later	--------------- Vendor data Equipment Process coordination Turn key
	Chemical milling	*Requirement*	Can be performed at various stages, but increases difficulty of other processes -------------------------- PE & MH Process features: Area thickness Area thickness tol Area location tol	TBD	---------------------- Vendor data Equipment Process coordination Turn key
	Plating	*Requirement*	After milling Before hardening Can be performed at various stages, but increases difficulty of other processes ------------------------- PE & MH Features: Area thickness Area thickness tol Area location tol	After major milling After hole processing After specialty processing During initial Detail Fabrication instead of returned later	Vendor data Equipment Process coordination Turn key

Table 7.9 RIM-Diagram for Forming Group: 7 of 9

R I M T, R, S	**Manufacturing Capabilities by Work Center**	**COMMON Manufacturing Selective Anticipation Features**	**COMMON Technical Process Capabilities Limitations**	**COMMON Technical Process Rules and Preferences**	**NEW (Future)** In-house planning --------------------- Vendor data
	Wash/Clean		Before shot peening ------------------------- PE & MH Req usually based on another process Limited technical significance		Not likely outsourced as a stand-alone process
	Shot peen	*Requirement*	Can be performed at various stages, but increases difficulty of other processes ------------------------- PE & MH Contour definition Features: Area thickness Area thick tol Area loc tol	After major milling After hole processing Before heat treat During initial Detail Fabrication instead of returned later	Test patterns and published results First article test part ----------------------- Vendor data Equipment Process coordination Turn key

Note: Group numbers and work centers are from lower-level CBS, Figure 7.4

Table 7.10 RIM-Diagram for Marking and Quality Assurance Groups: 8 and 9 of 9

R I M T, R, S	**Manufacturing Capabilities by Work Center**	**COMMON Manufacturing Selective Anticipation Features**	**COMMON Technical Process Capabilities Limitations**	**COMMON Technical Process Rules and Preferences**	**NEW (FUTURE)** In-house planning ----------------- Vendor data
	Vibroengrave		After plate mill After major milling Limited technical significance ----------------------- PE & MH Extra marking based on “fracture critical” requirement		NA
	Stamp		Last step before leaving Detail Fabrication Limited technical significance		NA
	Plate inspection		First step in processing sequence ------------------- Extra Inspection based on “fracture critical” requirement	NA	Coordination of requirements ----------------- Coordination of requirements
	Non-destructive inspection (NDI)		After major milling	NA	Coordination of requirements ----------------- Coordination of requirements
	Intermediate inspection		After special hole processing coatings, hardening or special treatment, chemical processing, forming	NA	Coordination of requirements ----------------- Coordination of requirements
	Final inspection		Last step in the processing sequence	NA	Coordination of requirements ----------------- Coordination of requirements

Note: Group numbers and work centers are from lower-level CBS, Figure 7.4

The results of the discussion of manufacturing engineering responsibilities and RIM-diagramming efforts in Section 7.9.2 are the conceptual information hierarchies for: 1) manufacturing selective anticipation features, 2) technical process capability limitations, 3) technical process rules and preferences, and 4) manufacturing engineering studies. The first three items are the titles of the three common columns in Tables 7.3 through 7.10. Item 4 is a result of the "New column" discussed in Section 7.9.2 and the first "Common column" in Table 7.2 (page 193), which deals with manufacturing engineering information silos.

Figure 7.14 is a conceptual representation of a portion of manufacturing engineering information hierarchies utilized by the DSS.

- ME Technical Information
  - Work center number
    - Machines (studies) *(First common column, Table 6.2)*
    - Equipment (studies) *(First common column, Table 6.2)*
    - Portable systems (studies) *(First common column, Table 6.2)*
    - TBD (studies) *(First common column, Table 6.2)*
    - Manufacturing selective anticipation features *(First common column, Tables 6.3 – 6.10)*
    - Technical process capabilities limitations *(Second common column, Tables 6.3 – 6.10)*
    - Technical process rules and preferences *(Third common column, Tables 6.3 – 6.10)*
  - Benchmarking (TBD)
  - Suppliers (TBD)
    - New processes (TBD)
    - New machines/equipment (TBD)

Work center number allows association with other information

Not linked to in-house work centers, but still of potential interest to other users of technical information; will have query capability in the DSS

Figure 7.14 Conceptual Manufacturing Engineering (ME) Technical Information Hierarchies

The conceptual framework presented in this research does not include the information hierarchies required for RIM of the Assembly activity due to scope and timeframe considerations. However, before continuing with further discussion related to NC machining efforts, RIM-diagramming of assembly tasks are briefly discussed to provide some insights as to the difficulty of the future effort. The discussion is based on this author's work experience and is relevant because typically the assembly load sequence is the first information considered by the working level IPT because all schedules are based on the delivery date of final assembly.

Table 7.11, offered on the next page, is based on the assumptions: 1) the assembly of the design is performed in-house and 2) the "assembly processes" are those associated with "mechanical subassembly." Unlike "Detail Fabrication," where a design is routed through multiple work centers (i.e., processes), in Assembly, routing of a design is not based on process, but product structure. One operator (or a group of operators) performs "multiple assembly processes" in one work center until an "assembly" of the product structure is completed. The design is typically routed to another work center for buildup into the "next higher assembly" configuration, until it ultimately reaches final assembly. Final assembly correlates to the "Airframe" level on the product structure in Figure 6.1

Assemblies are completed in multiple-series as structural details are located and joined, i.e., not all drilling is performed, and then all fasteners installed. The structural build-up series utilized is based on the concurrent consideration of assembly information, such tolerance requirements, hole location requirements, material stack up thickness, and fastener specification requirements.

Table 7.11 Partial/Beginning RIM-Diagram for Assembly Processes Sequencing and Capabilities

	Assembly Sequence	**COMMON** **Part Type + Next Structural Part Considerations**	**COMMON** Subassembly (Typically one major structural part plus simple details)	**COMMON** Component Assembly (Typically several major structural parts)	**NEW** In-house planning --------- Vendor data
R I M	***Detail remains in one work center***	General considerations are the same whether in Subassembly or Comp assembly	Parts + Subassembly Fixture	Parts + Component Assembly Fixture *More likely in the critical path*	TBD
	Obtain detail Load detail			***TBD***	***TBD***
	Locate (up/down) Locate (side/side)	Bulkhead feature Pin part-to-part ------------------------ Assembly tool plus shim Layout plus shim	***Preferred***		
	Secure detail				
	Hole processing	Pattern established Hole location tolerance Part back-drill Pinned tool ------------------------ Assembly tool Template mark Layout Min Process Req Fastener type Hole dia tol Material stackup type Material stackup thickness	*Preferred* More expensive Hole location tolerance *Prefer "easier" fasteners*		
	Disassemble Deburr holes Reassemble				
	Install fasteners				
	Install systems related items – clips/brackets		*Pushes release earlier*		
	Electrical bonding Other	***If not done in detail fabrication***			

Multi-series processes are those identified between the blue arrows. Each design repeats these processing in different patterns. The series can be complete one or more times, based on a design's unique requirements.

Assembly is not being incorporated into the DSS at this time due to the level of complexity

As discussed earlier in Section 7.5.1, it is unlikely all detail parts for a complex component are loaded into an assembly fixture, drilled, and mechanically fastened all at once due to tolerance considerations. In actuality, the addition of detail parts to an assembly build-up is complex, and the correct sequencing of steps is the most difficult aspect of modeling mechanical subassembly tasks. Due to this complexity, specific assembly considerations are planned future work.

Table 7.11 provides additional insights with regard to a "manufacturing selective anticipation feature" which has not been previously discussed, "Subassembly type." If the conceptual framework in Chapter 7 included a complete definition of the Assembly activity (i.e., IDEF0 diagram Activity 8), then this "manufacturing selective anticipation feature" would require identification and demonstration. "Subassembly type" is necessary to address the various configurations (i.e., installation drawings) in which a bulkhead is assembled. For example:

- Installation of nutplates or bushings to a bulkhead
- Buildup of a bulkhead subassembly in a floor-based fixture. Typically additional structural members are fastened to the bulkhead.
- Utilization of a bulkhead with other major structural parts in a component assembly
- Utilization of a bulkhead with other major structural parts in a final assembly (i.e., aircraft buildup in one-fixture)

"Subassembly type" is designated as a "manufacturing selective anticipation feature," since manufacturing engineering is typically responsible for the manufacturing plan and "manufacturing selective anticipation features" convey preferences to the Engineering activity. However, when EBOM=MBOM (as stipulated in Section 7.3) the members of the IPT are required to agree on the breakdown of installation drawings, or a "drawing tree" of next assembly relationships.

Based on the previously defined "design selective anticipation features" in Figure 7.8, page 207, the information in the RIM-diagram in Table 7.11 has the most technical significance with regard to subassembly.

In Detail Fabrication work centers (Figure 7.4, page 181) the CBS is nearly synonymous with "process." In that, a design in Detail Fabrication is moved from from work center to work center (i.e., process to process). However, in subassembly/assembly installation sequencing the design, in general, is not routed but remains for processing.

Hence, the work center CBS (Figure 7.3, page 180) in assembly typically accommodates groups according to the product structure or type of design. For example, an assembly work center designation may be "Forward subassembly" or "Bulkhead subassembly." The CBS designation within the Assembly activity depends on how management wishes to organize similar task groups.

In the beginning RIM-diagram for assembly, Table 7.11, the reciprocal interdependencies of "Technical, Resources, and Sequencing" are being considered concurrently. The information presented in this diagram is based upon this author's work experience, as no literature could be located containing specific aircraft related explanation.

The first column is titled "Assembly Sequence" and is similar to Detail Fabrication process. The second column labeled "Common Part Type plus Next Structural Part Considerations," conveys that the NC machined bulkhead is a first load item - and therefore already located/oriented utilizing the assembly fixture - and considerations of the next structural part are being examined.

The first step that an operator performs is to “Obtain” the detail design, and then “Load” the detail into the assembly fixture. The next step is to “Locate” the detail design in the fixture in multiple directions. For simplicity, the locating process is listed as up/down and side/side. There are multiple ways to locate a detail and the method presented is for simplicity.

One way to “Locate” the next detail design is to use internal bulkhead features, such as a shelf or stiffener. (Common aircraft nomenclature is discussed in Appendix B.) For example, if a fuel floor is located using a shelf internal to a bulkhead, then the fuel floor is positioned in one direction by being placed flush (i.e., net tolerances) against the shelf. However, this action does locate/position the fuel floor in another direction. A second method of locating the next structural detail in relation to a bulkhead is to utilize a part-to-part pinning procedure. In order to pin-locate two detail structural parts, both details must have tooling holes drilled during Detail Fabrication or just prior to the locating procedure. These two methods are typically the most preferred methods.

A third method of locating the next detail in relation to a bulkhead is to utilize the assembly fixture, and shim any remaining gap between the next structural detail and the bulkhead. Lastly, the operator can manually layout the location of the second structural detail manually, and shim as required. The last two methods are the least preferred methods because they involve manual layout and shimming, which are more time intensive and lead to increased quality issues.

The next step listed in the assembly sequence column is “Secure.” Securing devices can be hand clamps, tooling clamps that are incorporated in the tool design, or other devices. Securing steps are not typically technically difficult.

After the details are secured, the next step is “Hole processing.” There are two primary considerations in hole processing, the establishment of the hole pattern and the tolerances on hole location. One method for establishing a hole pattern is by using a pre-drilled pattern on another detail part for back-drilling. Depending on the tolerance requirements, a tooling hole may be required to locate one hole in the pattern. A second method is the utilization of a pinned drill plate (tool). A third method for establishing the hole pattern and maintaining appropriate tolerances is the use of a tool that is built into the assembly fixture. Other methods include the operator making a template or laying out the patterns by hand.

The minimum requirements for hole processing are typically found in the specifications for the fastener to be installed in the hole. Hence, once the structural design engineer has determined the preferred fastener(s), the fastener specification information conveys the manufacturing minimum tooling requirements, provided the IPT members understand these relationships. Other considerations are material stackup type (e.g., aluminum-aluminum, aluminum-composite) and material stackup thickness. Thicker stackups and complex stackups typically lead to more complex tooling and hole processing systems.

The next processing steps are “Disassemble, Deburr, and Reassemble.” These are self-explanatory, and are not technically difficult.

The next step in the assembly sequence depends on the requirements of the job. If three detail structural parts share common fasteners, then the operator may stop here and start the sequence over by obtaining another detail. Or, the operator may be able to proceed to the installation of fasteners before adding more structural details to the assembly. These nuances are why there is a blue arrow between “Obtain,” “Load,” and “Install fasteners.” There are other complexities that vary from design to design that dictate the number of times this series of steps is repeated. The discussion of these complexities is planned for future research.

After “Install fasteners” comes “Install systems related items – clips/brackets.” Typically, holes for clips and brackets are drilled and their fasteners installed after the major structure is assembled. However, in some instances, these systems holes are drilled in the same step as other structural fastener holes, and all fasteners are installed at once. Again, it depends on other complexities, which is one of the reasons why assembly RIM-diagramming is more complex than Detail Fabrication where the process sequencing has easier to understand technical variations. The important thing for IPTs to understand is if systems clips and brackets are planned for installation in subassembly, then it pushes the Engineering activity (i.e., IDEF0 Activity 3, Figure 2.5, page 54) to release the designs related to the clips and brackets earlier than would be required to support a component assembly or final assembly installation.

The very last step in the assembly sequence is “Other.” Processes such as electrical bonding, form-in-place gaskets, simple painting, etc., are typically the very last tasks performed on a subassembly/assembly.

The fourth column of the partial assembly RIM-diagram deals with component assembly. While it is possible that a major structural subassembly might not be on the critical path, it is highly likely that a component assembly is on the critical path. The reason for modularizing subassemblies is to remove make span from the critical path of major assembly fixtures so that tasks may be performed in parallel. The rest of the partial assembly RIM-diagram is intentionally left blank. The definition of Assembly related decision making is not a part of this research, but is planned future work.

Now that assembly RIM-diagramming has been briefly discussed, it is time to redirect the discussion back to Detail Fabrication.

The "Technical processing systems information" presented in the columns titled, "Technical Process Capabilities Limitations" and "Technical Process Rules and Preferences" of the RIM-diagrams in Tables 7.3 through 7.10 are similar to the manufacturing engineering information that planners use to develop routing sequences and work instructions. This knowledge is initially determined by manufacturing engineering when the fabrication line is set up. An assumption of this research is manufacturing engineering develops and maintains the work center relationships in Tables 7.3 through 7.10 (i.e., process rules, process capabilities, and preferences) in a computerized fashion accessible by the DSS. Similarly, it is assumed manufacturing engineering develops and maintains manufacturing selective anticipation features by work center. (The cultural and behavioral implications of this assumption is discussed in a later section.)

A routing sequence by work center is the *framework* on which MES logic and information is structured. In order to manage the reciprocal interdependencies existing between the information in the MES from past designs and the new design being considered by the IPT, a consistent, assumption-based model is needed to simulate the fabrication planning/routing sequencing process that takes place after the design is released (i.e., during the design phase). In addition, the fabrication planning/routing sequencing simulation must initially require only the "design selective anticipation features" in Figure 7.8, page 207. The assumption-based model is referred to as the Feedforward Planning Model (FFPM) fabrication plan and is discussed in the next section.

The use of a "pseudo-routing sequence/process plan" is not a new technique, and this research is not suggesting that it is. The problem with current approaches is they are ad hoc in nature, lack consistency, and are not part of an overall, well-defined procedure that is useful to an IPT for multiple aspects of decision making. IPTs require a more holistic view of the IDEF0 activities and the routing sequence is merely a small piece of a very large information puzzle; a puzzle whose starting point is the "design selective anticipation features."

7.9.3 Beginning Framework of the Feedforward Planning Model (FFPM) Fabrication Plan

The complete complement of design information is not available during conceptual design, so a methodology for generating a routing sequence and fabrication plan cannot be utilized. However, the information gleaned from RIM-diagramming efforts and the resulting conceptual hierarchies defined thus far supports the development of a Feedforward Planning Model (FFPM) fabrication plan.

The inputs an IPT is expected to make to the DSS are presented in Figure 7.13 (page 222) and are repeated here in Figure 7.15 to improve presentation and discussion.

Design Processing Category = **NC Machining**

- Detail Type = **Bulkhead**
  - Material Type = **n**
  - Finished Weight (target) = **w**
  - Part Envelope
    - Length (longest) = **L**
    - Width (next longest) = **W**
    - Depth (shortest) = **D**
  - Surface area (two dimensional-one side, or 2D-1S) = **SA**
  - Service Life {= **fracture critical**}
  - Subassembly process = **mechanical fastening**

Figure 7.15 Processing Category and Design Selective Anticipation Features for a Mechanically Fastened NC Machined Bulkhead - IPT Inputs/Entries in Blue and Bolded (Repeat)

Based on IPT data entries/inputs of the “design selective anticipation features,” the FFPM assumption-based fabrication plan for a NC machined bulkhead with these features is selected by the DSS from information hierarchies of FFPM fabrication plans developed and maintained by manufacturing engineering. The conceptual information hierarchies are illustrated in Figure 7.16, and represent an addition to previously presented Figure 7.14 (page 237).

- ME Technical Information
  - Work center number
    - Machines (studies) *(First common column, Table 6.2)*
    - Equipment (studies) *(First common column, Table 6.2)*
    - Portable systems (studies) *(First common column, Table 6.2)*
    - TBD (studies) *(First common column, Table 6.2)*
    - Manufacturing selective anticipation features *(First common column, Tables 6.3 – 6.10)*
    - Technical process capability limitations *(Second common column, Tables 6.3 – 6.10)*
    - Technical process rules and preferences *(Third common column, Tables 6.3 – 6.10)*
  - Benchmarking
  - Suppliers
    - New processes
    - New machines/equipment
  - *ME FFPM fabrication plans*
    - *Complexity features explanations*
      - *Processing categories*
      - *Design selective anticipation features*
        - *Design type*
        - *Material type*
        - *Finished weight (weight range)*
        - *Design envelope (size range)*
        - *Surface area*
        - *Service life*
        - *Subassembly process*

Manufacturing engineering (ME) coordinates with the Fabrication activity ahead of need to develop FFPM fabrication plan/routing sequences by design type. These plans are updated and maintained by ME.

ME information contains information to allow linkage via the RIM-based DSS with the PDMS, tool design and control system, the MES, etc.

Figure 7.16 Conceptual Manufacturing Engineering (ME) Technical Information Hierarchies (Modified from Figure 7.14)

A conceptual FFPM assumption-based fabrication plan for a bulkhead is presented in Table 7.12. An explanation follows the table.

Table 7.12 Conceptual FFPM Fabrication Plan (Processing Sequence)

CBS WORK CENTER	**CBS PROCESSING DESCRIPTION**	**ASSUMPTIONS**	**DESIGN TOOLS**	**Make/ Buy**
CBS# Material receipt	Material receipt -plate(s)			
CBS# Plate inspection	Plate inspection	Both plates		
CBS# Marking	Vibroengrave	Both plates		
CBS# 3-Axis tooling holes	Tooling holes	Both plates	Tool Code	x
CBS# 3-axis milling	Plate surface mill	Both plates		
CBS# 5-axis milling	***1 Milling** Trial Run	Assume 5-Axis; 5-Axis High Speed is alternatve	Tool Code	x
CBS# Vapor degrease	Hand finish - clean			
CBS# Deburr	Hand finish - deburr			
CBS# Remove tooling tabs	Hand finish – tooling tabs			
CBS# Mark	Vibroengrave			
CBS# Non-destruction inspection	Quality assurance			
CBS# 5-axis milling	***1 Milling** 2nd Run	Line stop, 1,st or 2nd		
CBS# Vapor degrease	Hand finish - clean			
CBS# Deburr	Hand finish - deburr			
CBS# Remove tooling tabs	Hand finish – remove tooling tabs			
CBS# Mark	Vibroengrave			
CBS# Non-destruction inspection	Quality assurance			
CBS# xxx (Proration) Drilling/Boring Type 1 Drilling/Boring Type 2	***2 Special hole processing**	Likely	Tool Code	x
CBS# 3-axis tooling holes	***2 Tooling (or coordinated) holes**	Likely	Tool Code	x
CBS# Intermediate inspection	Quality assurance			
CBS# xxx (Proration) Hardening and/or Special Treatment Chemical processing Forming	***3 Other special processing**	Not as likely; assumed due to risk		
CBS# Electrical bonding	Electrical bonding*	Assumed until otherwise specified		
CBS# Mask	Mask	Same as above		
CBS# Prime	Prime	Same as above		
CBS# Paint	Paint	Same as above		
CBS# Final inspection	Quality assurance			
CBS# Mark	Stamp			
		Most Likely Tools	**4**	
COMPLEXITY FEATURES				
Requirement critical and schedule critical	*3 Heat treat			
Same as above	*3 Chemical milling		*Tool Code*	x
Same as above	*3 Plating		*Tool Code*	x
Same as above	*3 Annodize			
Same as above	*3 Forming		*Tool Code*	x
*2 Special hole processing & coordinated holes	If not done in fabrication, detail part goes down, but assembly cost goes up			
Typically not schedule critical, in that, the design is already planned for milling Schedule setback allowances are measured in days and milling time is measured in hours	*1 Milling Technical capabilities are addressed prior to start using published capability limits and test patterns on the machine	Technical risk factors can be worked well in advance of design release	*Possible additional tools = 3*	

Tool codes are linked via the Tool design classification and control system

Note: the actual work center number is associated with the CBS work centers numbers in Figure 7.4

Make or Buy status is discussed later and come from Make/Buy Policies conceptual information

All NC machined bulkheads are routed through the work centers listed in the top section of this table

Table 7.12 is beginning to resemble a combination of a project plan and a routing sequence. The table contains a processing sequence by CBS, manufacturing assumptions related to the process sequencing, and a general approach to handle first-article schedule risk. This research assumes that manufacturing engineering organizes and defines technical information and develops FFPM fabrication plans, which are coordinated with the management of the Fabrication activity (i.e., IDEF0 Activity 7, page 56). Until the IPT interjects and documents additional information or assumptions to justify changes, the FFPM fabrication plan retrieved by the DSS for a design based on its "selective anticipation features" is utilized. Having a pre-defined starting point facilitates computer support of the decision-making process and assures information congruency between decision makers.

The FFPM fabrication plan presented in Table 7.12 is not intended to be the "end all" for fabricating an NC machined bulkhead but is intended for illustrative purposes only. A premise/assumption conveyed in Table 7.12 is that a trial run is planned for the first-article. (This type of assumption would be based on historical data and schedule risks associated with missing the assembly load date of a bulkhead.) If the trial run is successful, then the second detail is machined. If neither plate produces a production design, then it is likely a *line stop*. Since bulkheads are typically first load items, when they are late the entire assembly line schedule experiences negative schedule performance impacts until a work-around plan is identified and implemented.

Another assumption in Table 7.12 is the utilization of the "5-Axis milling" work center, as opposed to the "5-Axis milling high speed" work center. There are multiple reasons why this assumption is valid; but the technical rationale is not as important as the establishment of consistent assumptions that are clearly conveyed to decision makers. Similarly, a trial run is part of the FFPM fabrication plan, and if the trial run is successful, both plates are used to create details assignable to an aircraft.

"Manufacturing Selective Anticipation Features" relative to the "5-Axis Milling" work center include internal design features (e.g., shelves, stiffeners, etc.) and holes to locate other structure. These are the features most desired by manufacturing and are previously identified in Table 7.3 - RIM-Diagram for NC Milling Group: 1 of 8, page 224. Similarly, the DSS utilizes manufacturing engineering information hierarchies conceptually represented in Figure 7.16 to convey the importance of these features.

Since internal locating features have been used in the past, it is not unreasonable to assume some complement of locating features is identifiable on the current design. However, in order for this assumption to be realized, the IPTs working on other major structural detail designs sharing common fasteners with the bulkhead must coordinate with the bulkhead IPT to develop a plan for achieving the goal. The DSS cues the IPT that these locating features are a priority, as bulkheads are typically the first designs released.

"Special hole processing" and "Tooling (coordination) holes" are assumed in the FFPM fabrication plan in Table 7.12 because of the likelihood of locating other structural parts by referencing to the bulkhead and manufacturing's desire to do so to reduce assembly labor hours and/or tooling costs. Again, now that the "manufacturing selective anticipation features" have been assumed, the designers working on structural details sharing common fasteners with the bulkhead must ascertain a method to make this anticipated opportunity a reality. The determination of the method is typically considered in conjunction with assembly sequencing tasks.

If holes related to systems installations (i.e., clips, brackets, studs, etc.) are identifiable, then they can be processed during these same hole processing steps as the structural fastener holes. However, the identification of systems holes will not significantly impact the detail fabrication hole processing labor hours or schedule; but instead improve assembly installation costs. The schedule setback (makespan) for hole processing work centers in detail fabrication is measured in days while the processing time for most holes is in seconds. (Adding a few more to an estimate of labor hours makes little difference once the work center is on the routing sequence and allowed for in the schedule.) While manufacturing would prefer to drill holes related to systems installations concurrently in the same work center with other structural fastener holes, the main driver as to whether these tasks can occur concurrently is the coordination of the design release schedules between structural designers and the associated systems designers.

“Special hole processing” can be accomplished in multiple work centers, so a placeholder is designated on the FFPM fabrication plan. Based on historical data, a work center strategy is developed to prorate over multiple areas until the design becomes more “firm.”

“Other special processing” is a placeholder at this time in Table 7.12, i.e., the FFPM fabrication plan. It represents “Heat treat, Heat treat age, Chemical milling, Forming, Plating, and Annodizing.” The preference is to avoid special processing but, from a project planning perspective, it adds too much schedule risk to assume that no special processing will be required until the design is more firm. Hence, a compromise is needed for this item that is based on historical data. Initially, a prorated work center strategy is used. (A proration strategy involves scheduling tasks across similar work centers when it is uncertain as to which one specifically will be utilized.)

The baseline assumption is that "Electrical bonding" associated tasks are performed in Detail Fabrication because it is more cost effective to mask off an area and prevent it from being painted, as opposed to an operator sanding off the paint later prior to systems installation. Electrical bonding is normally performed in areas where systems designers have identified the need. Hence, coordination with designers working on systems is required to avoid moving the entire task to the assembly area. If the IPT decides that it is not reasonable to plan for electrical bonding surface preparation to be accomplished on the bulkhead while in Detail Fabrication, then this step can be removed from the FFPM fabrication plan by the IPT and added to the installation/assembly plan, and ultimately the design drawing. Another consideration of the electrical bonding surface preparation process is the tolerance on the location of the electrical bond surface. The location tolerance should be relaxed enough for an operator to lay it out by hand, or additional time will need to be planned into the schedule to utilize a tool. If a tolerance on location requires tooling, then the tool design requirement and tool manufacturing time will have to be allowed for in the schedule, and this will consequently push the release of the installation drawing earlier.

The baseline plan in Table 7.12 assumes that "Mask, Prime, and Paint" are performed while in Detail Fabrication. If a design is not going to be painted in detail fabrication, then a specific plan for painting the detail must be determined well in advance. Routing a major structural part from an assembly area to a detail design painting work center is typically not preferred.

"Complexity" is discussed in the bottom section of Table 7.12, and coordinated to the top section of the table with yellow highlighted numbers. The top section of Table 7.12 contains processes performed on all NC machined bulkheads, and the bottom section contains processes performed only on some machined bulkhead. It is not enough to discuss complexity as *easy, average, or difficult* because these are terms not directly assignable to a specific CBS, process, tool, etc. without technical explanation. Instead, "complexity" is discussed in terms of the CBS work centers (i.e., processing steps) requiring the most diligent consideration.

The first type of complexity features is associated with "Milling" and is highlighted with the number *one*. Milling complexity is addressed by utilizing published capability limits and test patterns. Even though NC milling receives a great deal of attention in the literature, the risks associated with NC milling can be mitigated with a good test plan and by running test samples. The risks associated with failing to identify locating features that assist with the assembly tasks are much more difficult to quantify.

The second type of complexity features deals with hole processing capability and is highlighted with the number *two*. The importance of special hole processing has been previously discussed in the context of RIM-diagramming. The third type of complexity features deal with other special processing and is highlighted with the number *three*. These five items are highlighted with the number *three* in the bottom section of Table 6.12, (i.e., Heat treat, Chemical milling, Plating, Annodize, and Forming) and are "requirement critical" and "schedule critical."

Two of the most common mistakes made by estimators are the oversimplification of complexity and dealing of it on the basis of factors as opposed to the identification of processing requirements. In addition, there is often the assumption that complexity is *bad* or to be avoided, when in actuality, the nature of complexity is - *it depends*. A design that is more complex to mill quite often has locating features that save assembly time. Similarly, deferring holes from being drilled in fabrication makes the fabrication cost decrease, but the assembly costs increase. In addition, if the design requires plating, forming, or heat treatment for a valid technical reason, then it just does, and it not good or bad per se. The most important consideration of complexity is that key decision makers understand the technical need for the complexity and the implications to labor hours, machine hours, and schedule setback.

The “Design Tools” column on Table 7.12 contains information extracted from the previously defined tool classification and control system, i.e. the “Tool Code” requirements by work center. Once the work center number is established for the routing sequence, then the work center number provides the knowledge linkage to the tool classification and control system data to estimate tool code requirements.

The *estimating* segment of the tool classification and control system contains information by work center for the different types of tool codes historically required for a similar design. Recall these estimating data from the bottom segment of Figure 7.11.

The conceptual DSS logic automatically interfaces the tool codes by work center information and the beginning *make or buy* status of the design tool. For now, the make or buy information is designated as a placeholder, x, in the “Make/Buy” column of Table 6.12. The *make or buy* information hierarchies are discussed later in Section 7.14.

The FFPM provided by the DSS to the IPT is a starting point only and a framework of discussion. The IPT can keep the plan or edit as they see fit. Based on this author's work experience, it is far easier to engage individuals in editing a plan than creating a plan from scratch. The important this is that the IPT will consider the tasks required to make better decisions, and ultimately, those decisions will be stored in a work center based format that other downstream users of information both recognize and accept.

7.9.4 Recap of Decision Making Supported Thus Far

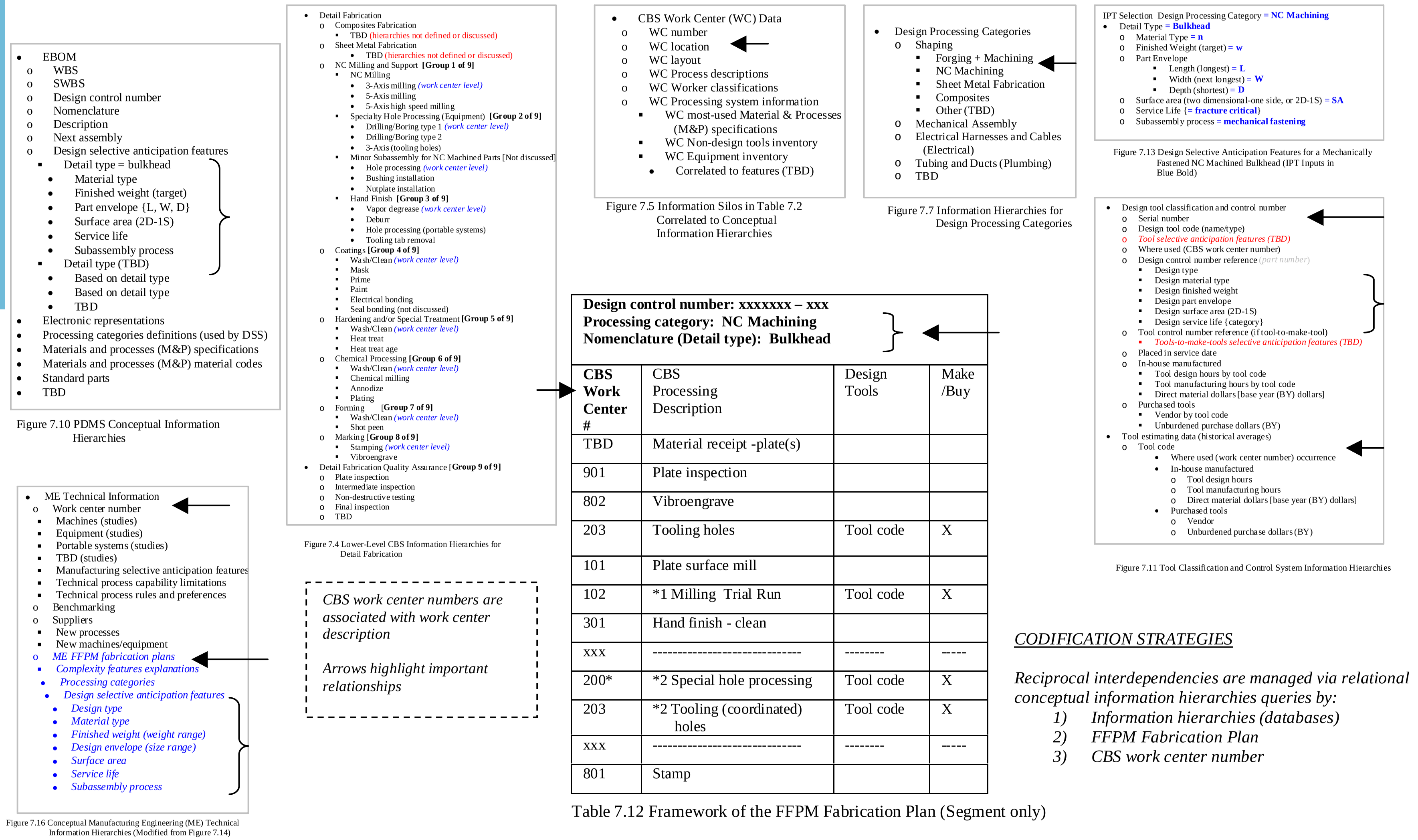
Before continuing further, it is important to recap the conceptual RIM-based codification of information hierarchies discussed thus far. Recall from Chapter 1, page 32, codification involves the systematic classification and storage of knowledge to address predefined questions and issues.

The relationships discussed thus far are offered in Figure 7.17. A partial section of Table 7.12 is provided. In the first column is titled, "CBS work center number." This work center designation corresponds to a work center number assigned to the CBS work center hierarchies in Figure 6.4. Typically work center numbers have both unique and numerical narrative descriptors.

In order to improve understanding, a partial CBS work center description and work center number identifier association is offered in Table 7.13.

Table 7.13 Examples of CBS Work Center Numbers

Group	Cost Center	Work Center Description in Figure 7.4	CBS Numerical Identifiers
NC Milling and Support			
	NC Milling		100
		3-Axis milling	101
		5-Axis milling	102
		5-Axis high speed milling	103
	Specialty Hole Processing		200
		Drilling/Boring type 1	201
		Drilling/Boring type 2	202
		3-Axis tooling holes	203
	Hand Finish		300
		Vapor degrease	301
		Deburr	302
		Hole processing (portable systems)	303
		Tooling tab removal	304
Coatings			400
		Wash/Clean	401
		Mask	402
		Prime	403
		Paint	404
		Electrical bonding	405
		Seal bonding	406
(others processed skipped)			
Marking			800
		Stamping	801
		Vibroengrave	802
Detail Fabrication Quality Assurance			900
		Plate inspection	901
(others processed skipped)			



- EBOM
  - WBS
  - SWBS
  - Design control number
  - Nomenclature
  - Description
  - Next assembly
  - Design selective anticipation features
    - Detail type = bulkhead
      - Material type
      - Finished weight (target)
      - Part envelope {L, W, D}
      - Surface area (2D-1S)
      - Service life
      - Subassembly process
    - Detail type (TBD)
      - Based on detail type
      - Based on detail type
      - TBD
- Electronic representations
- Processing categories definitions (used by DSS)
- Materials and processes (M&P) specifications
- Materials and processes (M&P) material codes
- Standard parts
- TBD

Figure 7.10 PDMS Conceptual Information Hierarchies

- ME Technical Information
  - Work center number
    - Machines (studies)
    - Equipment (studies)
    - Portable systems (studies)
    - TBD (studies)
    - Manufacturing selective anticipation features
    - Technical process capability limitations
    - Technical process rules and preferences
  - Benchmarking
  - Suppliers
    - New processes
    - New machines/equipment
  - *ME FFPM fabrication plans*
    - *Complexity features explanations*
      - *Processing categories*
      - *Design selective anticipation features*
        - *Design type*
        - *Material type*
        - *Finished weight (weight range)*
        - *Design envelope (size range)*
        - *Surface area*
        - *Service life*
        - *Subassembly process*

Figure 7.16 Conceptual Manufacturing Engineering (ME) Technical Information Hierarchies (Modified from Figure 7.14)

- Detail Fabrication
  - Composites Fabrication
    - TBD (hierarchies not defined or discussed)
  - Sheet Metal Fabrication
    - TBD (hierarchies not defined or discussed)
  - NC Milling and Support **[Group 1 of 9]**
    - NC Milling
      - 3-Axis milling *(work center level)*
      - 5-Axis milling
      - 5-Axis high speed milling
    - Specialty Hole Processing (Equipment) **[Group 2 of 9]**
      - Drilling/Boring type 1 *(work center level)*
      - Drilling/Boring type 2
      - 3-Axis (tooling holes)
    - Minor Subassembly for NC Machined Parts [Not discussed]
      - Hole processing *(work center level)*
      - Bushing installation
      - Nutplate installation
    - Hand Finish **[Group 3 of 9]**
      - Vapor degrease *(work center level)*
      - Deburr
      - Hole processing (portable systems)
      - Tooling tab removal
  - Coatings **[Group 4 of 9]**
    - Wash/Clean *(work center level)*
    - Mask
    - Prime
    - Paint
    - Electrical bonding
    - Seal bonding (not discussed)
  - Hardening and/or Special Treatment **[Group 5 of 9]**
    - Wash/Clean *(work center level)*
    - Heat treat
    - Heat treat age
  - Chemical Processing **[Group 6 of 9]**
    - Wash/Clean *(work center level)*
    - Chemical milling
    - Annodize
    - Plating
  - Forming [**Group 7 of 9]**
    - Wash/Clean *(work center level)*
    - Shot peen
  - Marking [**Group 8 of 9]**
    - Stamping *(work center level)*
    - Vibroengrave
- Detail Fabrication Quality Assurance [**Group 9 of 9]**
  - Plate inspection
  - Intermediate inspection
  - Non-destructive testing
  - Final inspection
  - TBD

Figure 7.4 Lower-Level CBS Information Hierarchies for Detail Fabrication

CBS work center numbers are associated with work center description

Arrows highlight important relationships

- CBS Work Center (WC) Data
  - WC number
  - WC location
  - WC layout
  - WC Process descriptions
  - WC Worker classifications
  - WC Processing system information
    - WC most-used Material & Processes (M&P) specifications
    - WC Non-design tools inventory
    - WC Equipment inventory
      - Correlated to features (TBD)

Figure 7.5 Information Silos in Table 7.2 Correlated to Conceptual Information Hierarchies

- Design Processing Categories
  - Shaping
    - Forging + Machining
    - NC Machining
    - Sheet Metal Fabrication
    - Composites
    - Other (TBD)
  - Mechanical Assembly
  - Electrical Harnesses and Cables (Electrical)
  - Tubing and Ducts (Plumbing)
  - TBD

Figure 7.7 Information Hierarchies for Design Processing Categories

Design control number: xxxxxxx – xxx
Processing category: NC Machining
Nomenclature (Detail type): Bulkhead

CBS Work Center #	CBS Processing Description	Design Tools	Make /Buy
TBD	Material receipt -plate(s)		
901	Plate inspection		
802	Vibroengrave		
203	Tooling holes	Tool code	X
101	Plate surface mill		
102	*1 Milling Trial Run	Tool code	X
301	Hand finish - clean		
xxx	------------------------------	--------	-----
200*	*2 Special hole processing	Tool code	X
203	*2 Tooling (coordinated) holes	Tool code	X
xxx	------------------------------	--------	-----
801	Stamp		

Table 7.12 Framework of the FFPM Fabrication Plan (Segment only)

IPT Selection Design Processing Category **= NC Machining**

- Detail Type **= Bulkhead**
  - Material Type **= n**
  - Finished Weight (target) **= w**
  - Part Envelope
    - Length (longest) **= L**
    - Width (next longest) **= W**
    - Depth (shortest) **= D**
  - Surface area (two dimensional-one side, or 2D-1S) **= SA**
  - Service Life {**= fracture critical**}
  - Subassembly process **= mechanical fastening**

Figure 7.13 Design Selective Anticipation Features for a Mechanically Fastened NC Machined Bulkhead (IPT Inputs in Blue Bold)

- Design tool classification and control number
  - Serial number
  - Design tool code (name/type)
  - *Tool selective anticipation features (TBD)*
  - Where used (CBS work center number)
  - Design control number reference *(part number)*
    - Design type
    - Design material type
    - Design finished weight
    - Design part envelope
    - Design surface area (2D-1S)
    - Design service life {category}
  - Tool control number reference (if tool-to-make-tool)
    - *Tools-to-make-tools selective anticipation features (TBD)*
  - Placed in service date
  - In-house manufactured
    - Tool design hours by tool code
    - Tool manufacturing hours by tool code
    - Direct material dollars [base year (BY) dollars]
  - Purchased tools
    - Vendor by tool code
    - Unburdened purchase dollars (BY)
- Tool estimating data (historical averages)
  - Tool code
    - Where used (work center number) occurrence
    - In-house manufactured
      - Tool design hours
      - Tool manufacturing hours
      - Direct material dollars [base year (BY) dollars]
    - Purchased tools
      - Vendor
      - Unburdened purchase dollars (BY)

Figure 7.11 Tool Classification and Control System Information Hierarchies

<u>CODIFICATION STRATEGIES</u>

Reciprocal interdependencies are managed via relational conceptual information hierarchies queries by:

1) *Information hierarchies (databases)*
2) *FFPM Fabrication Plan*
3) *CBS work center number*

Figure 7.17 Recap of DSS Conceptual RIM-Based Codification Discussed in Sections 7.0 Through 7.9

Figure 7.17 provides a representation of the reciprocal interdependencies managed thus far. The RIM-based FFPM facilitates the communication of a consistent baseline of assumptions for manufacturing a new design. In addition, if a member of an IPT does not have a wide range of experience, the DSS potentially provides a wealth of information to "educate/train" the user with respect to processes information, specifications, tools, and equipment.

Recall from Chapter 5 (Section 5.2) the types of decisions the IPT members are required to make. The information developed thus far supports many potential IPT decisions. For example, the planner and the manufacturing engineer assigned to an IPT can begin to forecast how many tool orders, tool designs, and work instructions packages are likely required. The IPTs are also cued to focus on which designs require close coordination, in particular, the detail parts potentially located in reference to the design in question or share common fasteners with the design in question.

Another example would involve the identification of a "design selective anticipation feature" that was outside of the capabilities limits maintained by manufacturing engineering. The "new" equipment, processes, and supplier information provide a good source of preplanning knowledge to begin identifying opportunities for new technology insertion.

Before moving on to the next section, it is necessary to recap the information development thus far in the context of the RIM-based knowledge construction yet to be defined. Previously provided Figure 7.12 (page 217) is updated as Figure 7.18 to show defined segments color-coded in black and yet to be defined segments in blue italics.

The “Feedforward Planning Model” will not be colored in black until the reciprocal interdependencies “Resources” and “Sequencing” are developed.

- Design Processing Categories **(Section 7.7)**
  - o Product Data Management System (EBOM/Product Structure) **(Section 7.3; 7.8.2)**
    - ▪ Features [$\text{Features}_{\text{DesignSelectiveAnticipation (Mfg)}}$ + $\text{Features}_{\text{ManufacturingSelectiveAnticipation (Design)}}$] **(Section 7.8.1; Figure 7.8)** **(Section 7.9.2)**
      - *Feedforward Planning Model (FFPM)*
        - o CBS Work Centers **(Section 7.4.2)**
          - **#1** ▪ Technical processing systems information
            - M&P standards and specifications by work center **(Section 7.6)**
            - Equipment inventory **(Section 7.8)**
              - o Equip specs correlated to $\text{Features}_{\text{DesignSelectiveAnticipation (Mfg)}}$ + $\text{Features}_{\text{ManufacturingSelectiveAnticipation (Design)}}$ + $\text{Features}_{\text{DesignOther(Mfg)}}$
            - Manufacturing Engineering studies by work center **(Section 7.6)**
            - Specific processing capabilities limits [$\text{Features}_{\text{DesignSelectiveAnticipation(Mfg)}}$ $\text{Features}_{\text{ManufacturingSelectiveAnticipation(Design)}}$] **(Section 7.9)**
            - Design specific tooling used on past designs (historical data by product by type, i.e., part of tool classification and control system) **(Section 7.8.2)**
              - o Tool codes (Tool Type; $\text{Features}_{\text{DesignSelective anticipation (Mfg)}}$)
              - o Tools to make tools on past designs
                - ▪ Tool features (Will not be addressed)
            - Non-design specific tools (located in the areas, such as portable hole processing systems) inventory **(Section 7.6)**
          - **#2** ▪ *Resources (management strategy)* (overhead not discussed)
            - *Direct labor hours (touch)* **(Section 7.10)**
            - *Machine hours* **(Section 7.10)**
            - *Direct labor hours (other)* **(Section 7.10)**
            - *Procurement dollars* **(Section 7.10)**
          - **#3** ▪ *Sequencing (scheduling/availability)*
            - *Sequence decisions based on the management of existing requirements (already planned for other products)* **(Section 7.11)**
              - o *Labor hours by shift by timeframe* **(Section 7.11)**
              - o *Machine hours by shift by timeframe* **(Section 7.11)**
            - *Technical sequencing considerations linked with the Master Schedule (internal scheduling)* **(Section 7.12)**
            - *Sequencing decisions based on management of new requirements by work center (incomplete designs)* **(Section 7.13)**

Highlighted numbers refer to capability contexts discussed in Section 6.5.

Figure 7.18 RIM Development Conceptual Framework (Update of Figure 7.12)

Figure 7.18 provides a means of organizing the development of the conceptual framework within the previously defined contexts of “capability,” (i.e., technical, resources, and sequencing). It is not to be confused with the designation of conceptual information hierarchies for the purposes of codification - Figure 6.16 is offered for that purpose.

In the next section, the segment of Figure 7.18 titled “Resources” is developed.

7.10 Resources

In this section the approach for developing the information hierarchies of the "Resources" segment of Figure 7.18 are offered. First, feedforward planning concepts from Verganti's study are discussed. Next, RIM concepts are used to identify the potential problems with current approaches and opportunities for common knowledge exchange. Finally, the framework utilized by the conceptual DSS is presented for direct labor and machine hours, direct labor (other/non-touch), procurement dollars, and dollarization of resources using rates. (Dollarization is used in the context of real dollar pricing and includes conversions related to base year dollars, then year dollars, inflation, and currency conversion for contractual or financial reporting.)

7.10.1 Feedforward Planning Concepts from Verganti's Study of Teaming/IPTs

In Verganti's study, at least two concepts are pertinent to the "Resources" aspects of feedforward planning: early process engineering and superficial anticipation. These concepts and related aircraft manufacturing implications are discussed in the next two sections.

7.10.1.1 Early Process Engineering

Verganti's study reveals the anticipation of constraints and opportunities entails collection and organization of large amounts of information - in particular information related to process engineering and manufacturing. In the context of teaming and feedforward planning, several companies performed these tasks well; but most fell short in transferring early decisions to subsequent users of information. Subsequent users of information typically *start over* and develop ad hoc information to support decision making because the information needed for decision making is not made available from upstream developers/users.

As discussed in Chapter 5, page 115, an employee of Raytheon published a report on IPT utilization. (Rickman, 2001.) This document states that in order to get an "understandable and achievable" (it is assumed the author meant task-oriented) schedule and cost for their products, IPTs had to develop and take responsibility for meeting schedule and cost targets. Schedule and cost targets both utilize resource estimates of direct labor and machine hours as primary building blocks of information. The IPTs at Raytheon were required to generate low-level tasks and associated resource requirements to make schedules easier to manage and more accurate.

Rickman's report implies that even though programmatic schedules and cost estimates had already been developed, they were not in a format IPTs could use effectively. Hence, the transfer of knowledge from Business Management estimating and proposal activities to the IPTs did not occur.

Based on this author's work experience, another type of transfer typically does not take place. Once IPTs develop information, it is not transferred to the manufacturing execution system (MES), and conversely, information from past endeavors stored within the MES does not feedforward to the IPTs. The labor and machine hours requirements used to manage shop floor activities is generated by the MES work measurement system – not from IPT estimates. There is, for all practical purposes, no direct link between the work measurement system values and IPT values.

7.10.1.2 Superficial Anticipation

Verganti's study reveals another problem associated with ineffective feedforward planning, superficial anticipation. Superficial anticipation occurs when decisions rely heavily upon undocumented assumptions. Verganti reports most that enterprises who are successful in feedforward planning efforts incorporate checkpoints along with the teaming/concurrent engineering process in order to verify completeness of upstream solutions for downstream users. Once the checkpoints are verified, solutions are not allowed to change without going through a traceable change process.

The Raytheon experience documented by Rickman (2001), as well as this author's experience, supports the assertion that superficial anticipation takes place in the defense industry. If a baseline of checkpoints had been established, then IPTs would not be required to "start over" in their assessment for resources management. Further, Wynn et al. (2005) presents the results of a six-month study conducted by Massachusetts Institute of Technology to identify the root causes of poor performance in defense acquisition programs. The findings indicate three major problems exist, which correlate to Verganti's definition of superficial anticipation: 1) the inability to breakdown planned work to be accomplished and correlate to estimates of cost and schedule, 2) scope creep due to poorly defined baselines, and 3) measurement systems' inability to generate the necessary feedback for corrective action.

7.10.2 RIM-Diagramming of Labor and Machine Hours

This section offers a RIM-diagram (Table 7.14) that highlights some issues related to the development of direct labor and machine hours information. Discussion discussed follows the presentation of the RIM-diagram.

Table 7.14 RIM-Diagram for Resources (Labor and Machine Hours)

Labor and Machine Hours	COMMON Conceptual	COMMON Conceptual/ Preliminary	COMMON Detail (First-Article)	COMMON Detail (Production)	NEW In-house ---------- Suppliers
			Knowledge from detail design systems to IPT		
TECHNICAL Developer	Business Mgmt estimating	**IPTs**	Factory Mgmt MES	Factory Mgmt MES	ME, WM ----------- TBD
Goals	Cost engineering	Requirements development (limited mgmt)	Requirements development and mgmt	Process management	TBD
Focus	Estimating focus	IPT project requirements focus **NOT WELL DEFINED**	Task focus at CBS level Schedule control Hours control Schedule reduction focus	Task focus at CBS level Schedule control Hours control Hours reduction focus	TBD
Tools	Parametrics CERs Models		Type 2 standards (CBS work center averages)	Type 1 standards Feature-based system applied at CBS level	WM studies
Type of estimate	Focus on "did take"		Focus on "should take"	Focus on "should take"	TBD
Learning curves	Learning curves		No learning curves	No learning curves	TBD
Factors	Efficiency factors (high-level)		Efficiency considered at CBS work center level for personnel forecasting	Efficiency considered at CBS work center level for personnel forecasting	TBD
RESOURCE (organization of information)	High-level Department and/or CBS		Detailed; must include all CBS work centers	Detailed; must include all CBS work centers	Must identify new CBS work centers
SEQUENCING					
Process internal (overlaps with process technical)	Buried in CERs or estimating spreads		Work measurement studies	Work measurement studies	Work measurement studies
Process-to-process (overlaps with process technical)	Buried in CERs or estimating spreads				
Availability (scheduling)	Assumed		MES capacity planning system once requirement is identified	MES capacity planning system once requirement is identified	MES logic changes

The RIM-diagram is organized into six columns. The first column deals with the RIM categories of technical, resource, and sequencing as in other RIM-diagrams.

The second column is titled, “COMMON Conceptual.” This column designates the relevance of commonality information in the context of direct labor and machine hours during conceptual design, in particular the time when the original bid is developed.

The third column is titled, “COMMON Conceptual/Preliminary.” This column specifies the implications of commonality information in the context of direct labor and machine hours during conceptual design when working-level IPTs begin to be utilized as well as the preliminary design phase.

The fourth column is titled, “COMMON Detail (First-Article).” This column designates the application of commonality information in the context of direct labor and machine hours during the detail design phase, in particular the manufacturing of the first-article.

The fifth column is titled, “COMMON Detail (Production).” This column designates the implications of commonality information in the context of direct labor and machine hours during the detail design phase, in particular the manufacturing of units beyond the first-article.

The sixth column is titled, “NEW.” It designates the labor and machine hours information that are required to make decisions on totally new processes to be done in-house or by suppliers. Before reviewing the “Common” columns on the RIM-diagram, the “New” column is first discussed.

If a “new” requirement is identified, then a plan is needed (i.e., preplanning knowledge) for addressing the new requirement. As discussed earlier in Section 7.9, enterprises typically successful in feedforward planning also dedicate considerable effort to developing “preplanning knowledge.” There are many tasks an IPT could perform that do not require a finished design; but individual IPT members quite often do not realize their accomplishment is necessary or possible. The envisioned DSS provides a checklist of tasks for IPTs to consider, and the checklist constitutes a significant step toward automating “preplanning knowledge.” If the overall *plan* assumes these “new” processes can be found in the absence of appropriate preplanning knowledge, then the result is superficial anticipation.

The technical aspects of “new” processes and the role of manufacturing engineering are discussed earlier in Section 7.9. In Section 7.10, the role of work measurement studies is discussed. In order to make a meaningful decision with regard to new processes, the work measurement group should be brought into the discussions to develop appropriate information earlier in the decision making process. (Jiao and Tseng, 1999.) Based on this author’s work experience, the work measurement group is typically not involved until a manufacturing job (i.e., routing/planning sequence) is loaded into the MES and standard data are often not developed for “new” processes until production. In other words, the decisions related to the selection of “new” processes are made before a complete work measurement analysis has been performed.

If a “new” process is to be performed in-house, then a great deal of preplanning effort is necessary in order to bring the process online efficiently. Examples of questions best addressed by the IPT in advance include:

- Will the process be incorporated into an existing CBS work center or is an entirely new work center needed?

- Are special security clearances or worker classifications required?
- How much floor space and how many personnel?

In addition, if a new CBS work center is required, then it leads to the necessity for multiple systems changes. Examples of changes include:

- The cost ledger (cost accounting logic) within the Business Management activity
- Routing logic within the Planning activity
- Scheduling, pricing, and performances logic within the MES
- Work measurement application logic for generation of standard values
- Factory Management tables that control personnel, capacity, performance reporting, etc.

Based on this author's work experience, many IPT members - and even project managers - do not fully understand the level of detailed effort required to successfully load and monitor a job order in the MES.

If a "new" process is to be performed by a vendor, then a determination has to be made as to whether any in-house direct labor hours will be required to support receipt of the detail design. In addition, the details of how a new vendor is incorporated into enterprise systems have to be worked out in advance.

Next, a discussion of information in the "Common" columns is offered. The first row of "Technical" information is titled "Developer." These parties are involved in estimating labor and machine hours for decision making. The first developer (Common Conceptual column) of resource information during conceptual design is the estimating group within the Business Management activity (i.e., Chapter 2, IDEF0 Activity 1, Figure 2.4, page 53).

Continuing to move across the row, the next developers (Common Conceptual/Preliminary column) are the IPTs. The IPTs become responsible for the resources information during conceptual design, and continue to be responsible during preliminary design. It can be argued that “super IPTs” actually develop the cost estimates prior to contract award (as discussed in Chapter 5, Section 5.1) as opposed to a Business Management estimating group developing the estimates without assistance from other activities on the IDEF0 diagrams; but this distinction really does not matter. At some point in the process, when tasks are segmented to working-level IPTs, the problems discussed earlier with information exchange exist.

The next “developer” (Common Detail First-Article column) is the Factory Management manufacturing execution system (MES). When a job/order is released to the MES, it goes through a job scheduling and pricing (work measurement) routine typically not influenced by any prior IPT decision making. The work measurement system assigns standard hours and the scheduling system assigns CBS load dates based on pre-determined routines.

The next “developer” (Common Detail Production column) is also designated as the Factory Management MES. This additional column is added to make the distinction between what typically happens on the first-article and what happens later on during production.

The last “developer” in column six is designated as manufacturing engineering (ME) and the work measurement (WM) group for in-house “new” processes and TBD for “new” processes performed by suppliers.

The second row under “Technical” is designated as “Goals.” The goal of Business Management is typically “cost engineering.” Cost engineering should have as its foundation the identification of requirements and a clearly defined baseline; but according to Verganti’s study and others cited earlier, too many requirements are buried in assumptions due to superficial anticipation.

Cost engineering efforts are supposed to result in business planning and project management information. However, in the current state, a “cost estimate” is being developed that fulfills the objectives of Business Management, but the information needs of downstream users are not being supported. (Previously discussed in Chapter 1, Section 1.1.1.3, page 8.) If these information needs were being met, then working-level IPTs would not “start over” to develop new estimates. Further, checkpoints to validate the information requirements of downstream users/systems are not clearly identified.

The primary goal of the working-level IPT is requirements development. In this diagram, the requirements/resources are direct labor, machine hours, and related procurement. Once requirements are developed, estimates of schedule and cost are derived from these requirements. The IPT is involved with enterprise-level requirements management in a limited fashion, but typically do not coordinate their tasks with other programs/projects until the design is released to the MES.

The goal of the Factory Management MES on the first-article is requirements development and management. Once a job is planned in the MES, the information related to this job and all other jobs are combined to provide a complete picture of the direct labor and machine hours requirements for the enterprise for any given timeframe.

In column five, the goal of the Factory Management MES during production changes slightly. Even though the MES still manages requirements, it takes on a new role of "process management." The MES becomes a tool for process improvement.

The third row under "Technical" is designated as "Focus." This row is similar to the second row. The main distinction worth noting is that on the first-article, schedule reduction is usually the focus, while on subsequent units, labor hours reduction becomes the focus.

The fourth row under "Technical" is designated as "Tools." Business Management utilizes parametrics, cost estimating relationships (CERs), and models to generate a baseline; but the baseline is typically not easily understood by subsequent users or particularly supportive of their decision making needs. For example, providing a numeric value of "nonrecurring tooling dollars" does not provide insights into how many tools are required, the tool codes, or why they are believed to be required. (If the baseline were understood, then working-level IPTs would not need to regenerate estimates for cost and schedule as discussed in Chapter 5.) Business Management still uses approaches that do not incorporate the process and sequencing knowledge available from the work measurement system. If they are, then this knowledge is likely buried and is not *transferred* to the working-level IPTs. For example, instead of providing an estimate the work center level where capacity and manning tables are maintained, estimating just provides a total hours required for NC machining. This research assumes that feature-based type 1 standards are available (or can be developed) from past or ongoing production endeavors' work measurement studies. (Type 1 and type 2 standards are common industrial engineering terms and are discussed further in Section 7.10.4.)

The fifth row under "Technical" is designated as "Type of estimate." A "did take" focus is an actual hours emphasis. A "should take" focus is a process-based approach that emphasizes the number of direct labor hours a task "should take" based on standard data. The MES does not load jobs/orders based on actual hours expended; but instead uses standard hours available from the work measurement system.

The sixth row under "Technical" is designated as "Learning curves." The MES does not load jobs using values based on learning curves. Again, work measurement standard values are used.

The seventh row under "Technical" is designed as "Factors." The MES does not load jobs using values derived from Business Management estimating factors. Again, standard values are used. Instead, efficiency and shift considerations are applied to develop personnel forecasts. Efficiency, per se, is incorporated into the personnel forecasts (e.g., manning tables). (Rai, 2004.)

The second section in Table 7.14 is designated as "Resource (organization and information)." While Business Management can prevail with estimating information at high-levels - the MES cannot operate effectively with this level of detail. In order for the MES to function properly, *all* CBS work centers must be identified.

The third major section (or eighth row) of Table 7.14 is designated as "Sequencing." This row is quite complex because it is "multidimensional" and difficult to properly illustrate in tabular format. The row contains some "technical process information" specific to sequencing as well as availability/scheduling information.

During early conceptual design, important information is often buried in CERs and not transferred to IPTs. However, once a design begins manufacture, work measurement data begins to be applied, and information from past work measurement studies are utilized. If a process is “new,” the work measurement group develops new studies to fully describe the process. The technical information in these work measurement studies is potentially valuable to decision makers, but typically they are not available in a format easily usable by IPT members.

7.10.3 Conclusions Related to Table 7.14

The RIM-diagram in Table 7.14 illustrates several disconnects in the development of “resources” estimates. The same CBS work centers which have performed processes on past designs are going to be performing them again on the design being considered, yet the enterprise is foregoing many of the known benefits of using a work measurement system. In addition, the information transfer problems previously discussed in Section 7.2, page 167, which led to the use of EBOM=MBOM from a technical design perspective are similarly occurring with regard to resources estimates information. There are disconnects in “the white spaces where the baton is passed.” (Rummler and Brache, 1995.)

Since the information exchange with the RIM-based DSS, thus far, is geared toward features and processes, one of the best sources of information for the DSS and the IPTs is the work measurement system.

7.10.4 The MES Work Measurement System

The benefits of work measurement are well documented in the literature. With today's increasing global competition, there has been a resurgence of interest in work measurement founded on scientific methods rather than estimates based on judgment and experience. Work measurement system (WMS) values are the primary building blocks utilized in shop floor scheduling, capacity requirements planning, and earned value management systems (EVMS). (Salvendy, 2001.)

A report issued by the Office of the Undersecretary of the Defense cited that EVMS reporting is often of little value on new programs because: 1) tasks are not well defined, 2) the WMS is not fully integrated, and 3) interdependencies between IPTs tasks and the Master Schedule are not well defined. (USOUSD, 2000) Further, in a study sponsored by the Department of Defense, the Software Engineering Institute (SEI) cited one of the problems with EVMS is insufficient attention is paid to the base measurements on which the earned value is built. (SEI, 2002.)

This research assumes the MES utilizes a feature-based WMS to develop standard values. It is important to note, a "standard value" is not one value applied to all conditions or forever. A "standard value" is based on a set of conditions and assumptions for the intended use of the value. A type 1 standard value, as defined in Handbook of Industrial Engineering: Technology and Operations (Salvendy, 2001), is the result of defining the resources a task "should take," not what it "did take," under a set of defined ground rules and parameters. (Aft, 2000; Salvendy, 2001.)

This research assumes the WMS supporting the MES contains feature-based, type 1 standard values and associated process knowledge, which can be reused for the purpose of conceptual design decision making. Specifically, the specified reuse strategy is linked to the consideration of "Features" as defined in Section 7.8, i.e.,

$\text{Features}_{\text{DesignSelectiveAnticipation(Mfg)}} + \text{Features}_{\text{ManufacturingSelectiveAnticipation(Design)}} + \text{Features}_{\text{DesignOther (Mfg)}}$.)

The next section discusses the additional assumptions required for the utilization of RIM-strategies to restructure the WMS data.

7.10.5 Key Assumptions Related to the Work Measurement System

This section lists six key assumptions related to the WMS. Where appropriate, additional explanations are offered as to the relevance of the assumption.

1) The WMS is feature-based and has sensitivity to features used to estimate labor hours resources requirements.

If the WMS used in the MES is based on some other approach, then it is difficult to develop a DSS to provide meaningful feedback with regard to the relationships between features and resources (e.g., labor and machine hours).

2) Feature-based time values are derived from lower-level process analysis that includes job-sequencing considerations.

If feature-based time values are derived from actual hours, then the sequencing information is unintentionally *buried* in the actual hours and not easily restructured. For example, a feature-based value derived from process analysis for hole drilling is based on where the drill was obtained, the setup procedure, the steps involved in processing, etc. A feature-based time value derived from actual hours alone cannot restructure the steps or provide lower-level detail visibility to process performance. In order to manage process-specific reciprocal interdependencies, they must be considered within each step of data development.

3) Work measurement data is restructured/grouped to be sensitive to design selective anticipation features only, but still maintain traceability to specific assumptions utilized in the development of restructured/grouped values.

The grouped standard values returned by the DSS are calculated using design selective anticipation features. Once a consistent standard value baseline is defined, then it can be revised and improved upon using actual hours and variance analysis. This approach offers a tremendous improvement over various "cost estimators" utilizing their own ad hoc approaches. (As previously discussed in Chapter 4, Section 4.2, page 105.)

4) The work measurement data can also be applied in a more detailed fashion using additional features within the set of $\text{Features}_{\text{DesignOther(Mfg)}}$.

During conceptual design, the only features known with relative certainty are the "design selective anticipation features." Once the design is complete, or nearly complete, the "design other manufacturing features" can be input to the DSS to calculate a standard value equivalent to the standard value that the WMS generates when a job order is released to the MES. This detailed information is helpful in decision making during conceptual/preliminary design and prior to detail design release.

5) There are historical data available that can be used to study relationships based on the identified design selective anticipation features, i.e., by design type, material finished weight, part envelope (L,W,D) surface area (2-D,1-S) at the CBS work center level. The application of "commonality" means that similar processes have been used in the past. Now that design selective anticipation features have been

defined, there is a requirement to feedforward historical information utilizing design selective anticipation features.

   a. If the historical data are not easily obtainable via electronic records, then work measurement engineers develop relationships using various sources of information to create a representative sample from which to make initial decisions.

   b. If the historical data are not easily obtainable via electronic records, then required changes to historical performance records are identified and made before the new design reaches the detail design phase.

   c. The performance of the WMS based on the restructured data is measured at the first available opportunity, and changes in the selective anticipation CERs are made accordingly.

6) The WMS clearly defines “standard value” in order to facilitate inferences to “standard value” in the context of theoretical unit #1.

Theoretical unit #1 (T1) is a value used in learning curve based estimating procedures. (Learning curve based estimating is not specifically discussed in this research, but reference materials are provided in Appendix B.)

In the next section, work measurement RIM-diagramming is discussed.

7.10.6 Work Measurement System RIM-Diagramming

The work measurement system RIM-diagramming effort is more difficult to understand than prior diagramming efforts presented thus far. The user must visualize reciprocal interdependencies discussed as “Technical, Resources, and Sequencing” in previous RIM-diagrams are being concurrently considered at the CBS work center level. In addition, the concepts of “commonality” and “new” are being used to *restructure/group* the work measurement data from a broader perspective of *what is the same* and *what is different* from work center to work center.

The work measurement engineer (or team of engineers) restructures process study information into segments/pieces based on several considerations, such as: 1) which features are preferred for standard value development, 2) what portion of the standard value is reasonably assigned using only design selective anticipation features, 3) what portion of the standard value is common to all designs (e.g., basic setup and obtaining prints), and 4) how to make allowances for not having specific features information with the least possible error in the estimated standard value.

A series of RIM-diagrams are offered to illustrate the thought processes a work engineer would go through in Tables 7.15 through 7.20. These RIM-diagrams are to be viewed as "working papers" and are not intended to offer every insight into the anticipated effort.

The RIM column on the diagrams implies that all reciprocal interdependencies are being considered on each row of the diagram. The "Work Center" column contains descriptions of the work centers already identified in the CBS. Additional discussion of the diagrams is offered following the diagrams.

Table 7.15 Work Measurement RIM-Diagramming Effort: 1 of 6

R I M	Work Center CERs	COMMON Routing and Material Handling *(Ingress/ Egress)*	COMMON Work Meas. Material Handling	COMMON Work Meas. Common Setup and Finish	COMMON Work Meas. Process Time and Data Application Sensitivity Group	Work Measurement Application Preferences
	5-Axis milling ***Utilize design selective anticipation features*** *View as working papers All RIM relationships not illustrated*	**Part size, finished weight,** security, doorways, aisles, availability of cranes and equipment, human factors, etc. ***(Part size = part envelope = L,W,D)*** *(Plate size = Part size+2 inches, then coorelate to standard plate sizes*	**Part size, weight**, use of available MH equipment, area specific variables (walking distances), worker assignment	Per occurrence items– obtaining work instructions, prints, labor transactions, putting on/removing special clothing/gear, machine first time setup – using areas specific variables (distances); final cleanup	**Design type, part size, material**, **etc** (grouping of information as opposed to specific application to an available design) Mgmt policy – operator charges during processing time **Design type** is used to further segment data and reduce estimate error **Design type** descriptor improves reuse of information Milling baseline where most capacity available	Finished NC program for WM Feeds and Speeds program. Hole processing features Can develop values based on sensitivity group that applies to all parts. Metal removal based on weight Can develop complexity factors for features such as corner radii, pockets that correspond to factory preferences
	3-Axis milling	Same as above	Same as above	Same as above	Same as above (Plates)	Same as above
	5-Axis high speed milling	Same as above	Same as above	Same as above	Used when complexity deems baseline assumption of "5-Axis milling" is not appropriate	Same as above
	Drilling/Boring type 1	Same as above except plate size	Same as above	Same as above	Same as above (outside of milling machine capability limits) -------------------- after milling	Quantity by **hole processing (HP)** capability Can develop values based on **Sensitivity Group (SG)** and **historical occurrence (HO)**
	Drilling/Boring type 2	Same as above	Same as above	Same as above	Same as above and type 1	Same as Drilling /Boring type 1
	3-Axis (tooling holes)	Same as above	Same as above	Same as above	Same as above (close tolerance holes for coordination) All designs at least once	Quantity by hole processing capability Can develop values based on SG & HO

Table 7.16 Work Measurement RIM-Diagramming Effort: 2 of 6

R I M	Work Center CERs	COMMON Routing and Material Handling	COMMON Work Meas. Material Handling	COMMON Work Meas. Common Setup and Finish	COMMON Work Meas. Process Time and Data Application Sensitivity Group	Work Measurement Application Preferences
	Minor subassembly (cold work)	Same as 3-Axis NC (tooling holes) in Table 6.14	Same as 3-Axis NC (tooling holes) in Table 6.15	Same as 3-Axis NC (tooling holes) in Table 6.15	Same as above but may not need sensitivity to size Used on subassemblies after milling	Quantity by HP capability Can develop values based on SG & HO
	Minor subassembly (bushings)	Same as above	Same as above	Same as above	Same as above but may not need sensitivity to size Used on subassemblies after milling	Qty by bushing type (bushing # conveys size and processing requirement by feature which has already been matched to the areas capability to install that type of bushing) Can develop values based on SG & HO
	Minor subassembly (nutplates)	Same as above	Same as above	Same as above	Same as above but may not need sensitivity to size Used on subassemblies after milling	Same as bushing Can develop values based on SG & HO
	Hand finish (clean)	Same as above	Same as above	Same as above	Same as above but likely not sensitive to material All parts get once	Actual surface area. Can develop values based on SG & HO Can develop CERs for estimated surface area
	Hand finish (deburr)	Same as above	Same as above	Same as above	Same as above and Clean.	Same as HF Clean
	Hand finish (hole processing)	Same as above	Same as above	Same as above	Same as above Subassembly & Rework	Same as Drilling Boring Type 1
	Hand finish (tooling tab)	Same as above	Same as above	Same as above	Same as above All parts get once	Prefer actual tooling tab configuration Can develop values based on SG & HO

Table 7.17 Work Measurement RIM-Diagramming Effort: 3 of 6

RIM	Work Center CERs	COMMON Routing and Material Handling	COMMON Work Meas. Material Handling	COMMON Work Meas. Common Setup and Finish	COMMON Work Meas. Process Time and Data Application Sensitivity Group	Work Measurement Application Preferences
	Mask	Same as 3-Axis NC hand finish tooling tab in Table 6.15	Same as 3-Axis NC hand finish tooling tab in Table 6.15	Same as 3-Axis NC hand finish tooling tab in Table 6.15	Same as above but likely not sensitive to material --------------------- Use if painting is required Use if electrical bonding is required Wash prior to	Prefer actual surface area to be masked Can develop values based on SG & HO
	Prime	Same as above	Same as above	Same as above	Same as above --------------------- Use if painting is required	Prefer actual surface area to be primed Can develop values based on SG & HO Can develop CER for estimated surface area
	Paint	Same as above	Same as above	Same as above	Same as above Assume based on probability of occurrence	Prefer actual surface area to be painted Can develop values based on SG & HO Can develop CER for estimated surface area
	Electrical bonding	Same as above	Same as above	Same as above	Same as above	Prefer actual surface area to be treated Can develop values based on SG & HO Can develop CER for estimated surface area
	Vapor degrease	Same as above	Same as above	Same as above	Same as above to start - but may not need sensitivity to material because operator may not charge labor during processing times Assume based on heat treatment -------------------- After milling	Prefer defined requirement and processing times Can develop values based on SG & HO Can develop relationship based on heat treat occurrence

Table 7.18 Work Measurement RIM-Diagramming Effort: 4 of 6

R I M	Work Center CERs	COMMON Routing and Material Handling	COMMON Work Meas. Material Handling	COMMON Work Meas. Common Setup and Finish	COMMON Work Meas. Process Time and Data Application Sensitivity Group	Work Measurement Application Preferences
	Heat treat	Same as Vapor degrease in Table 6.16	Same as Vapor degrease in Table 6.16	Same as Vapor degrease in Table 6.16	Same as above – but some processing time is not charged by operator Make assumptions based on probability of occurrence ----------------- Process after milling Wash prior to heat treat	Prefer defined requirement and processing times Can develop values based on SG & HO Can develop relationship based on heat treat occurrence Can develop CER for heat treat age occurrence
	Heat treat age	Same as above	Same as above	Same as above	Same as above – but some processing time is not charged by operator Make assumptions based on probability of occurrence ------------------ Process after milling Wash prior to heat treat age	Prefer defined requirement, surface area, and processing times Can develop values based on SG & HO Can develop CER for surface area
	Chemical milling	Same as above	Same as above	Same as above	Same as above	Prefer defined requirement, milled surface area, and processing time Can develop values based on SG & HO Can develop CER for estimates of chemically milled surface area

Table 7.19 Work Measurement RIM-Diagramming Effort: 5 of 6

R I M	Work Center CERs	COMMON Routing and Material Handling	COMMON Work Meas. Material Handling	COMMON Work Meas. Common Setup and Finish	COMMON Work Meas. Process Time and Data Application Sensitivity Group	Work Measurement Application Preferences
	Plating	Same as Chemical milling in Table 6.17	Same as Chemical milling in Table 6.17	Same as Chemical milling in Table 6.17	Same as above – but some processing time is not charged by operator ---------------- After milling Wash prior to	Prefer defined requirement, plated surface area, and processing time Can develop values based on SG & HO Can develop CER for estimates of plated surface area
	Shot peen	Same as above	Same as above	Same as above	Same as above	Prefer defined requirement, shot peen ed surface area, and processing time Can develop values based on SG & HO Can develop CER for estimates of shot peen surface area
	Wash	Same as above	Same as above	Same as above	Performed prior to specific processes	Prefer requirement Can estimate relative to other process occurrence using assumed surface area

Table 7.20 Work Measurement RIM-Diagramming Effort: 6 of 6

R I M	Work Center CERs	COMMON Routing Material Handling	COMMON Work Meas. Material Handling	COMMON Work Meas. Common Setup and Finish	COMMON Work Meas. Process Time and Data Application Sensitivity Group	Work Measurement Application Preferences
	Stamping	NA Stamping operator typically travels to the work center	Same as Wash in Table 6.18	Same as Wash in Table 6.18	Typically size and per occurrence critical only Perform prior to final inspection	Prefer defined requirement Can develop values based on SG & HO Estimate based on occurrence
	Vibroengrave	Same as above (except plate is considered)	Same as above	Same as above	Same as above to start - but may not need sensitivity to estimate labor due to small amount involved Instead occurrence is most critical	Prefer defined requirement Can develop values based on SG & HO Estimate based on occurrence
	Quality Assurance	Dependent upon type of inspection Some inspection requires design to travel to a special area, while other do not	Standards not applied to inspection task	Standards not applied to inspection task	Same as above - WM not applied to inspection task but for operator waiting ----------------- Plate inspect at beginning of job Intermediate inspect after milling and special processing (e.g. chemical milling, heat treat, shot peen, etc. Final inspection as last step	Prefer defined requirement Can develop values based on SG & HO Estimate inspection allowances based on occurrence

The “Routing and Material Handling” column is directed toward the consideration of moving the design between work centers. The RIM-diagramming effort illustrates the work measurement engineer has designated two types of material handling data: the physical constraints involved with routing/moving between work centers and the physical constraints involved with processing the design with the work center. Hence, these distinctions immediately lead the identification of a requirement for material handling ingress/egress limitation sources by CBS, which is an addition to the work center conceptual hierarchies illustrated in Figure 7.5, page 197.

Multiple types of material handling equipment, the door openings, aisles, overhead crane availability, etc. should be organized by CBS work center. The constraints of material handling should be considered before the design is complete. Based on this author's experience, this type of information is typically in information silos known only by experts working in facilities or the work center area. Figure 7.5 is updated as Figure 7.19.

- CBS Work Center (WC) Data
  - WC number
  - WC location
  - WC layout
  - Process descriptions
  - Worker classifications
  - *Material handling information*
    - *WC ingress/egress correlated to features*
  - Processing system information
    - Most used M & P Specs
    - Non-design tools
    - Equipment inventory
      - Correlated to features (TBD)

Figure 7.19 Information Silos Transformed Into Conceptual Information Hierarchies (Updated From Figure 7.5)

Continuing with the discussion of Tables 7.15 through 7.20, the "Routing and Material Handling" column also identifies the requirement for the work measurement group to develop a CER based on an assumption of plate size for the DSS to operate. In addition, once the actual plate size is known, a new CER is needed to incorporate the updated information.

The "Work Measurement Material Handling" column identifies two types of material handling variables; these are based on the design characteristics and the physical characteristics within the work center. For example, the weight is used to determine when an operator can be expected to move a design alone, when two persons are needed, or when other equipment is needed for assistance. This information can be used to develop a CER that is sensitive to a range of weight and design size combinations. The variables associated with the area are constant. For example, "obtain plate" may be a selection when a value is being developed for a specific design. Regardless of the design, the distance an operator travels to obtain the plate is dependent upon the work center variables, not the design per se.

The "Work Measurement Common Setup and Finish" column is related to per occurrence items that happen on a job regardless of the design characteristics. This type of information can be applied on a per occurrence basis.

The "Work Measurement Process Time and Data Application Sensitivity Group" column designates how information related to processing time is best grouped. This grouping is based on the selective anticipation features and how they can be combined and applied to minimize error.

The "Work Measurement Application Preferences" column in Tables 7.15 through 7.20 is used to organize general preferences and considerations by work center. For example, for 5-Axis milling, the work measurement engineer would prefer a complete design so the NC milling process time could be estimated using on a computer program of feeds and speeds related to the milling operation, as well as specific application based on hole processing features. However, the work measurement engineer has determined that it is appropriate to develop CERs by part type that will be used to estimate all NC machined jobs until "complexity features" are established. (Note that complexity features are defined in Table 7.12, page 249.) Similar designs by design type within the 90th percentile are used to establish a baseline for milling time. The remaining 10% is left out to avoid padding requirements over a large sample of designs.

The work measurement engineer strives to determine a mix of CERs that approximate the WMS standard values the system will assign to a complete design once released into the MES. In addition, the selection of the 90th percentile is a judgment based on review of historical data and can be changed based variance analysis or management direction. If the CER values are determined to be "too large," then variance analysis can be used to discover the "flaws" in CER assumptions, and can be easily changed if the application is consistent.

Table 7.21 illustrates a conceptual grouped standard CER application matrix for the 5-Axis milling work center. These CERs are used to estimate machine setup and run time for the 5-Axis milling work center. Each of the work centers in the FFPM fabrication plan has a unique set of CERs the DSS utilizes to calculate the standard hours for the design being reviewed by the DSS. These CERs form the basis of estimate for direct touch labor hours.

Table 7.21 Conceptual Work Measurement Application Matrix

CBS Work Center 5-Axis Mill	Material Type AL Setup	Material Type AL Run	Material Type TI Setup	Material Type TI Run	Material Type STEEL Setup	Material Type STEEL Run
Design Type 90th percentile Milling		Weight (lb) & Plate Size est. (L+2, W+2, D+2) *Per lb of material removed*		Weight (lb) & Plate Size est. (L+2, W+2, D+2) *Per lb of material removed*		Weight (lb) & Plate Size est. (L+2, W+2, D+2) *Per lb of material removed*
Other Run		Part Envelope & Weight Matrix *Per Occurrence*		Part Envelope & Weight Matrix *Per Occurrence*		Part Envelope & Weight Matrix *Per Occurrence*
Other Setup	Sm, Med, Lg, Ex Lg Per Occurrence		Sm, Med, Lg, Ex Lg Per Occurrence		Sm, Med, Lg, Ex Lg Per Occurrence	
Surface area (2D, 1S) Ranges – S, M, Lg, Ex-Lg						
Small Range (X-Y)	CER	CER_M + CER_O	CER	CER_M + CER_O	CER	CER_M + CER_O
Medium Range (X-Y)	CER	CER_M + CER_O	CER	CER_M + CER_O	CER	CER_M + CER_O
Large Range (X-Y)	CER	CER_M + CER_O	CER	CER_M + CER_O	CER	CER_M + CER_O
Ex-Large Range (X-Y)	CER	CER_M + CER_O	CER	CER_M + CER_O	CER	CER_M + CER_O

The IPT members are not required to utilize the CER matrix in Table 7.21. Instead, an IPT member inputs/enters the “design selective anticipation features,” and internal DSS logic automatically performs the calculations.

For example, assume that the IPT has made the required inputs/entries to the DSS of the design selective anticipation features, i.e., design type, weight, material type, part envelope, and two-dimensional, one-side (2D-1S) surface area, service life, and subassembly process. The DSS estimates the plate size as being two inches larger than the part envelope. Once the plate size is estimated, the calculation of the "pounds of metal removed (milled)" is based on beginning plate volume, the density of the material type, and the finished weight of the design. In addition, the DSS automatically determines the bulkhead size category (e.g., small, medium, large, or extra-large) based on the surface area (2D-1S). The "setup" columns in Table 7.21 indicate that the setup CER is applied per occurrence. The "run" columns of Table 7.21 indicate that a portion of the run CER is applied per occurrence and a portion is applied on a per pound basis. The CER_M designation refers to the 90th percentile milling value and the CER_O designation refers to the "Other Run."

There are many ways to develop CERs and Table 7.21 and the accompanying explanation for a bulkhead are provided as an example only. Based on the discussion of the work measurement system, the conceptual information hierarchies required for feedforward planning and operation of the RIM-based DSS are illustrated in Figure 7.20.

- Work Measurement
  - Work center number
    - Process studies
    - Material handling constraints based on design selective anticipation features
    - Grouped standard CERs sensitive to design selective anticipation features
    - Detail features-based standard values (sensitive to all features; for specific application to nearly complete design)
    - TBD

Figure 7.20 WMS Conceptual Information Hierarchies

7.10.7 Feedforward Planning Model

At this point it is necessary to recap the development of the DSS thus far and the additional IPT decisions supported by the DSS. Once the material handling database is created for each CBS, then the IPT can begin to identify problems and issues related to the physical constraints of the design, the physical constraints of the work center, and the availability of appropriate equipment.

In addition, the design selective anticipation features can be used to develop estimates of standard values by CBS for the conceptual design using grouped standard CERs. Further, once additional information is known or can be reasonably estimated, the estimated hours can be revised using additional manufacturing selective anticipation features and design other features.

Once the IPT can develop a *standard value* in a format suitable for the MES, a giant step toward has been taken with regard to load the MES with a planned requirement, i.e., a job or order. Further, if many working-level IPTs can do the same thing, then information once unavailable until much later in the product development process can be developed earlier. The benefits of loading the MES using a conceptual design release package are discussed in Section 7.13. Loading the MES allows line balancing and earlier discovery of bottlenecks.

7.10.8 Cultural Implications

In Chapter 1 (i.e., Section 1.1.1.4, page 9), the cultural problems related to changing how enterprises approach product development are discussed. Using work measurement during conceptual design would be a cultural shift for aircraft manufacturing enterprises because there has been a historical reluctance to fully utilize the potential of work measurement information. (Kapoor, 1990; Lyssy and Sharp, 1997.) Work measurement was forced upon the industry under MIL STD 1567A (Work Measurement, 03/11/1983), and contractors are still reluctant to utilize detailed information until production. Even though work measurement studies can be used on “common” processes, the reluctance exists nonetheless.

Donald Rumsfeld (1995) wrote a series of articles suggesting top-down estimating approaches were efficient for high-level estimating, but they were not effective in exposing inefficiencies in processes. The exposure of enterprise inefficiencies could only be achieved through a bottom-up work measurement based approach. The fear of inefficiencies exposure is the likely driver behind defense contractor reluctance.

With regard to contract estimating cultural issues, in aircraft manufacturing, many of the factors used by the Business Management activity to forecast indirect labor hours are based on direct labor (touch labor) hours. For example, if a 1:1 factor for “direct (touch) labor” to “direct engineering and other labor” is used, then for every 10 hours of “direct (touch) labor” estimated a corresponding 10 hours of “direct engineering and other labor” is estimated. A 1:2 factor results in an estimate of 10 hours of “direct (touch) labor” estimated a corresponding 20 hours of “direct engineering and other labor.”

In recent years three interesting phenomena are occurring: 1) the direct labor portion of total aircraft cost is decreasing, 2) the other segments of total cost are increasing, and 3) the cost and schedule overruns are rising. Table 6.21 is based on two studies of aircraft manufacturing cost in the defense industry, attributable to Rogerson (1992) and the other to Kloos (2007). When direct material is removed from the total cost percentage, it provides insights into how errors in direct labor estimates potentially affect other estimates. In the 1992 timeframe, when direct material is removed from the total, the ratios of “direct labor to direct engineering” and “direct labor to other direct” are 1:1 and 1:0.41, respectively. In 2007, when direct material is removed from the total, these ratios change ratios from 1:1 to 1.7:1 and 1:041 to 2.9:1. Hence, effects of error in direct labor estimates can cause a two or three fold increase in error in other segments of the estimate. Perhaps in time, there will be an increased interest in improving estimates of direct labor. However, at this point, only the envisioned DSS is conceptual.

Table 7.22 Aircraft Total Cost Percentages

	(Rogerson,1992)		(Kloos,2007)	
	Percent of Total Cost		Percent of Total Cost	
Direct Material	51.9		46.7	
Direct Labor	20.1		9.6	
Direct Engineering and Other	19.9		16.2	
Other Indirect	8.1		27.5	
Total	100.0		100.0	
	1989		2007	
Excluding Direct Material	Percent of Total Cost	Ratio to D.L.	Percent of Total Cost	Ratio to D.L.
Direct Material				
Direct Labor (DL)	41.8		18.0	
Direct Engineering and Other	41.4	1-to-1	30.4	1.7-to-1
Other Indirect	16.8	0.41-to-1	51.6	2.9-to-1
Total	100.0		100.0	

7.10.9 Resources – Direct Labor Hours (Other) and Procurement Dollars

In this section the approach used by the conceptual DSS to handle the reciprocal interdependencies existing for direct labor hours (other) that are not touch labor is discussed. Previously, in Sections 7.10.2 and 7.10.8, some of the problems arising from the development of labor estimates at a high-level and/or factoring estimates of other direct labor based on direct (touch) labor are discussed. In this section a discrete approach is described for estimating direct labor hours (other) so these problems may be avoided. In addition, a discrete approach is assumed to provide better feedback to the IPT in addition to a more manageable plan. An IPT cannot manage a total number of hours, but instead needs hours correlated to specific tasks to be performed based on a schedule. The management information need by the IPTs to manage their tasks is not fundamentally different from information needed to mange direct touch labor tasks in the factory.

In Chapter 5 (beginning on page 118), the working-level IPT members for this research are defined as:

- Structural design engineer (leader) *(direct labor-design deliverable)*
- Systems design engineer *(direct labor-design deliverable)*
- Test engineer *(direct labor-design deliverable)*
- Tool designer *(direct labor-tool design deliverable)*
- Planner *(direct labor-work instructions deliverable)*
- Manufacturing engineer *(direct labor-tooling model deliverable)*
- Manufacturing representative *(allocated to touch labor as supervision)*
- Purchasing representative *(allocated to direct material)*
- Cost representatives *(various; depends on program management) (overhead)*
- Quality assurance representative *(allocated as direct overhead)*

In the listing above, the structural design engineer (and engineers working for him/her) is classified as direct labor (refer to high-level CBS in Figure 7.2) and his/her measured deliverable is a design. Similarly, planners are classified as direct labor and deliverables associated with planning tasks are work instructions.

Depending upon the high-level CBS structure, some or all of the IPT members may be treated as direct labor. A sampling of IPT members are discussed in this section in the context of internal DSS logic.

Recall from Chapter 5, important aspects of IPT member decision making involve the determination of the number of deliverables (i.e., designs, work instructions, tool models, etc.) their respective activities are responsible for producing (i.e., Chapter 2, IDEF0 diagrams), including the associated number of labor hours and schedule days to produce each deliverable. These estimation tasks can be accomplished using rules and templates that provide the necessary knowledge links to the framework of the FFPM fabrication plan in Table 7.12, page 249.

Table 7.12 illustrates the fabrication plan for one detail design and it lists the requirements for four design tools by tool code and by CBS work center. For the purpose of illustration, it is assumed that two of the design tools are manufactured in-house (i.e., make), two design tools are purchased, (i.e., buy), and one of the in-house manufactured tools requires another tool for its manufacture. Based on these requirements, the following deliverables are projected by internal DSS logic:

- Detail designs – 1 *(based on 1 NC machined bulkhead)*
- Detail work instructions – 1 *(based on 1 per detail design)*
- Tool orders – 5 *(based on 2 make, 2 buy, 1 make tool-to-make-tool)*
- Tooling work instructions – (based on 2 + 1 = 3 *(2 make, 1 make tool-to-make-tool)*
- Tool models – 5 (electronic data) *(based on 2 make, 2 buy, 1 make tool-to-make-tool)*
- Tool designs – 2+1 = 3 *(based on 2 make, 1 make tool-to-make- tool)*

Based on the high-level CBS presented in Figure 7.2 (page 177) and the logic illustrated above, requirement for new conceptual information hierarchies to meet the information needs of the IPT are identified for estimation of non-recurring engineering and tool design direct labor hours. The new conceptual hierarchies are illustrated in Figure 7.21.

- Project
    - Design selective anticipation features
        - Detail design templates
            - Design hours
            - Work instructions hours
        - Tool code templates
            - Tool models hours
            - Tool design hours
            - Tool manufacturing work instructions hours

Figure 7.21 Non-Recurring Engineering and Tool Design Direct Labor Conceptual Information Hierarchies

Though not discussed previously, a *make or buy* decision supercedes the generation of the FFPM fabrication plan in Table 7.12 (page 249). (United States Office of the Secretary of Defense, 1997.) A make or buy policy (likely agreed upon during the proposal effort) established aircraft NC machined bulkheads are to be manufactured in-house.

At this point in the DSS development, it is necessary to *back track* to discuss make/buy policies in the context of detail designs and design tools.

Recall Table 7.12 contains the basic process sequencing by CBS work center in addition to the initial estimate of design tool requirements. There is a column at the far right titled “Make/Buy.” The beginning entry into this column originates from a segment of conceptual information hierarchies not previously defined, i.e., the “Make/Buy Polices Management” conceptual information hierarchies. A segment of these hierarchies are provided in Figure 7.22.

- Make/Buy Policies Management
    - Processing categories
        - NC machining (make)
        - Processing category x (make, buy)
        - Processing category y (make, buy)
        - TBD
    - Design type
            - Bulkhead xxx NC machining (buy)
            - TBD
    - Design Tools
        - Tool code y
            - Control number xxx (make)
        - Tool code z
            - Control number xxx (buy)
        - TBD
- Raw Materials
    - Material a
    - Material b
    - TBD

Note: x, y, xxx,y, z, a, an b are placeholders

Figure 7.22 Make/Buy Policies Management Conceptual Information Hierarchies

“NC machining” is designated an in-house make processing category. However, an exception for design number xxx is noted. Tool codes of type y are designated as “make,” while tool codes of type z are designated as “buy.” These conceptual hierarchies are for illustrative purposes only, and are not the emphasis of this research.

If the design, tool code, or raw material is designated as a “buy” item, then the DSS requires temporary values for estimated procurement dollars until a procurement representative obtains ROM quotes or final bids for the item. Project templates for these estimates are envisioned to be in conceptual information hierarchies maintained by procurement within Business Management. Conceptual hierarchies for this type of information are is provided in Figure 7.23.

- Raw Material
  - M&P material code
    - Plate
      - Standard sizes
        - Vendors
          - Cost (BY, unburdened $)
          - Order history (M-days)
        - Project templates
          - Project x
          - Cost (BY, unburdened $)
    - Bar stock
      - Same as plate
        - “”
    - TBD
      - Same as plate
        - “”
    - Tool Code
      - Where used
        - Design selective anticipation features
          - Standardized ranges
            - Vendors (historical data)
              - Cost (BY, unburdened $)
            - Project templates
              - Project x
              - Cost (BY, unburdened $)
  - ROM Quotes
    - Design number
    - Tool number
    - TBD
  - Final Bids
    - Design number
    - Tool number
    - TBD
  - TBD

Figure 7.23 Procurement Management Conceptual Information Hierarchies

7.10.10 Estimation and Dollarization of Resources

The Business Management activity (i.e., Chapter 2, IDEF0 diagrams, Activity 1) is responsible for estimating resources at the enterprise level, which includes dollarization of estimates for external reporting purposes. Business Management develops and maintains many types of information (Appendix B), including, but not limited to:

- Statement of work (SOW) definitions
- Work breakdown structure (WBS) definitions
- Cost breakdown structure (CBS) definitions
- Accounting month definitions (M-day calendars) for financial reporting
- Direct and indirect labor rates
- Overhead rates
- Estimating factors (as discussed in Section 7.10.8) for recurring and non-recurring elements of the high-level CBS (Figure 7.2, page 177)
- Learning curves

In order for the conceptual DSS to dollarize resources estimates and calculate total cost for the IPT, it requires data developed and maintained by Business Management. As discussed in Chapter 4 (page 105) and Chapter 5 (page 125), there are typically multiple activities and individuals involved in cost estimation during conceptual design. Most often, their primary tools are personalized spreadsheets containing Business Management data, which often contain mistakes or do not contain the most up-to-date information. One of the envisioned improvements provided by RIM-based DSS provides is consistent management of reciprocal interdependencies related to cost estimating data. Conceptual information hierarchies linked to the DSS are provided in Figure 7.24.

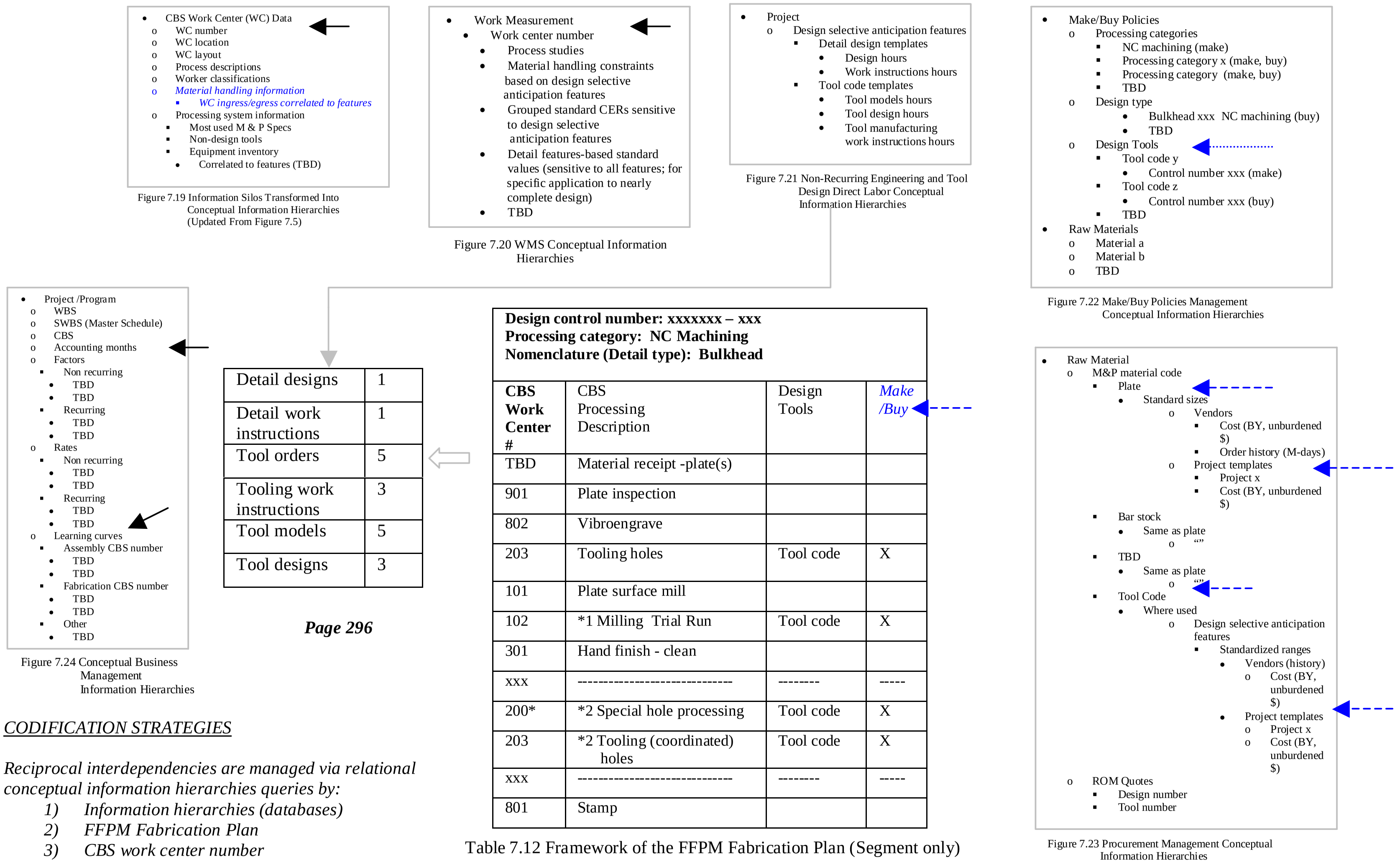
- Project /Program
  - WBS
  - SWBS (Master Schedule)
  - CBS
  - Accounting months
  - Factors
    - Non recurring
      - TBD
      - TBD
    - Recurring
      - TBD
      - TBD
  - Rates
    - Non recurring
      - TBD
      - TBD
    - Recurring
      - TBD
      - TBD
  - Learning curves
    - Assembly CBS number
      - TBD
      - TBD
    - Fabrication CBS number
      - TBD
      - TBD
    - Other
      - TBD

Figure 7.24 Conceptual Business Management Information Hierarchies

7.10.11 Summarization and Conceptual Framework and Information Hierarchies Updates

Before moving forward, it is important to recap the conceptual RIM-based codification of information hierarchies discussed in Section 7.10. Recall from Chapter 1, page 32, codification involves the systematic classification and storage of knowledge to address predefined questions and issues.

The relationships discussed in Section 7.10 are offered in Figure 7.25, which is an addition to Figure 7.17 (page 258).



- CBS Work Center (WC) Data
  - WC number
  - WC location
  - WC layout
  - Process descriptions
  - Worker classifications
  - *Material handling information*
    - *WC ingress/egress correlated to features*
  - Processing system information
    - Most used M & P Specs
    - Non-design tools
    - Equipment inventory
      - Correlated to features (TBD)

Figure 7.19 Information Silos Transformed Into Conceptual Information Hierarchies (Updated From Figure 7.5)

- Work Measurement
  - Work center number
    - Process studies
    - Material handling constraints based on design selective anticipation features
    - Grouped standard CERs sensitive to design selective anticipation features
    - Detail features-based standard values (sensitive to all features; for specific application to nearly complete design)
    - TBD

Figure 7.20 WMS Conceptual Information Hierarchies

- Project
  - Design selective anticipation features
    - Detail design templates
      - Design hours
      - Work instructions hours
    - Tool code templates
      - Tool models hours
      - Tool design hours
      - Tool manufacturing work instructions hours

Figure 7.21 Non-Recurring Engineering and Tool Design Direct Labor Conceptual Information Hierarchies

- Make/Buy Policies
  - Processing categories
    - NC machining (make)
    - Processing category x (make, buy)
    - Processing category (make, buy)
    - TBD
  - Design type
    - Bulkhead xxx NC machining (buy)
    - TBD
  - Design Tools
    - Tool code y
      - Control number xxx (make)
    - Tool code z
      - Control number xxx (buy)
    - TBD
- Raw Materials
  - Material a
  - Material b
  - TBD

Figure 7.22 Make/Buy Policies Management Conceptual Information Hierarchies

- Project /Program
  - WBS
  - SWBS (Master Schedule)
  - CBS
  - Accounting months
  - Factors
    - Non recurring
      - TBD
      - TBD
    - Recurring
      - TBD
      - TBD
  - Rates
    - Non recurring
      - TBD
      - TBD
    - Recurring
      - TBD
      - TBD
  - Learning curves
    - Assembly CBS number
      - TBD
      - TBD
    - Fabrication CBS number
      - TBD
      - TBD
    - Other
      - TBD

Figure 7.24 Conceptual Business Management Information Hierarchies

Detail designs	1
Detail work instructions	1
Tool orders	5
Tooling work instructions	3
Tool models	5
Tool designs	3

Page 296

Design control number: xxxxxxx – xxx
Processing category: NC Machining
Nomenclature (Detail type): Bulkhead

CBS Work Center #	CBS Processing Description	Design Tools	*Make /Buy*
TBD	Material receipt -plate(s)		
901	Plate inspection		
802	Vibroengrave		
203	Tooling holes	Tool code	X
101	Plate surface mill		
102	*1 Milling Trial Run	Tool code	X
301	Hand finish - clean		
xxx	------------------------------	--------	-----
200*	*2 Special hole processing	Tool code	X
203	*2 Tooling (coordinated) holes	Tool code	X
xxx	------------------------------	--------	-----
801	Stamp		

Table 7.12 Framework of the FFPM Fabrication Plan (Segment only)

- Raw Material
  - M&P material code
    - Plate
      - Standard sizes
        - Vendors
          - Cost (BY, unburdened $)
          - Order history (M-days)
        - Project templates
          - Project x
          - Cost (BY, unburdened $)
    - Bar stock
      - Same as plate
        - “”
    - TBD
      - Same as plate
        - “”
    - Tool Code
      - Where used
        - Design selective anticipation features
          - Standardized ranges
            - Vendors (history)
              - Cost (BY, unburdened $)
            - Project templates
              - Project x
              - Cost (BY, unburdened $)
  - ROM Quotes
    - Design number
    - Tool number

Figure 7.23 Procurement Management Conceptual Information Hierarchies

CODIFICATION STRATEGIES

Reciprocal interdependencies are managed via relational conceptual information hierarchies queries by:

1) *Information hierarchies (databases)*
2) *FFPM Fabrication Plan*
3) *CBS work center number*

Figure 7.25 Recap of DSS Conceptual RIM-Based Codification Discussed In Section 7.10

Previously presented Figure 7.18 (page 260) is now updated to reflect the information development of Section 7.10, and is provided as Figure 7.26

- Design Processing Categories **(Section 7.7)**
    - Product Data Management System (EBOM/Product Structure) **(Section 7.3; 7.8.2)**
        - Features [Features$_{\text{DesignSelectiveAnticipation (Mfg)}}$ + Features$_{\text{ManufacturingSelectiveAnticipation (Design)}}$]
          (Section 7.8.1; Figure 7.8) **(Section 7.9.2)**
            - *Feedforward Planning Model (FFPM)*
                - CBS Work Centers **(Section 7.4.2)**
                    - **#1** Technical processing systems information
                        - M&P standards and specifications by work center **(Section 7.6)**
                        - Equipment inventory **(Section 7.8)**
                            - Equip specs correlated to Features$_{\text{DesignSelectiveAnticipation (Mfg)}}$ + Features$_{\text{ManufacturingSelectiveAnticipation (Design)}}$ + Features$_{\text{DesignOther(Mfg)}}$
                        - Manufacturing Engineering studies by work center **(Section 7.6)**
                        - Specific processing capabilities limits [Features$_{\text{DesignSelectiveAnticipation(Mfg)}}$ Features$_{\text{ManufacturingSelectiveAnticipation(Design)}}$] **(Section 7.9)**
                        - Design specific tooling used on past designs (historical data by product by type, i.e., part of tool classification and control system) **(Section 7.8.2)**
                            - Tool codes (Tool Type; Features$_{\text{DesignSelective anticipation (Mfg)}}$)
                            - Tools to make tools on past designs
                                - Tool features (Will not be addressed)
                        - Non-design specific tools (located in the areas, such as portable hole processing systems) inventory **(Section 7.6)**
                    - **#2** Resources (management strategy) (overhead not discretely considered)
                        - Direct labor hours (touch) **(Section 7.10)**
                        - Machine hours **(Section 7.10)**
                        - Direct labor hours (other) **(Section 7.10)**
                        - Procurement dollars **(Section 7.10)**
                    - **#3** *Sequencing (scheduling/availability)*
                        - *Sequence decisions based on the management of existing requirements (already planned for other products)* **(Section 7.11)**
                            - *Labor hours by shift by timeframe* **(Section 7.11)**
                            - *Machine hours by shift by timeframe* **(Section 7.11)**
                        - *Technical sequencing considerations linked with the Master Schedule (internal scheduling)* **(Section 7.12)**
                        - *Sequencing decisions based on management of new requirements by work center (incomplete designs)* **(Section 7.13)**

Highlighted numbers refer to capability contexts discussed in Section 7.5.

Figure 7.26 RIM DSS Development Conceptual Framework (Update of Figure 7.18)

In the next section, the segment of Figure 7.26 titled "Sequence decisions based on the management of existing requirements" is developed.

7.11 Sequencing Decisions Based on the Management of Existing Requirements

In this section the information hierarchy related to the segment of Figure 7.26 titled “Sequencing decisions based on management of existing requirements” is presented. First, a general discussion of the manufacturing execution system (MES) is offered. Next, sequencing decisions within the context of capacity decisions are overviewed. Lastly, IPT decisions using the envisioned DSS are discussed.

7.11.1 Manufacturing Execution System (MES) Assumptions

The basics of personnel forecasting, requirements planning, and requirements scheduling are discussed in The Handbook of Industrial Engineering: Technology and Operations Management. (Salvendy, 2001.) Chapter 64 “Personnel Scheduling” and Chapter 78 “Advanced Planning and Scheduling Manufacturing” discuss a variety of algorithms commonly incorporated into computerized systems used for managing manufacturing requirements and resources, i.e., manufacturing execution systems. In general, the approaches presented in this research do not deviate significantly from commonly accepted practices discussed in the handbook.

In this research, a MES is assumed to be part of the Factory Management activity, (i.e., Chapter 2, IDEF0 diagrams, Figure 2.4, Activity 1, page 53). It is further assumed the primary purpose of an MES is to manage the labor and schedule requirements of manufacturing jobs (i.e., orders; not jobs in the context of employment). These requirements are broken into two major categories: 1) jobs that are currently being processed and 2) planned future jobs. In order to plan and manage a job within the MES, the requirements must be expressed in terms of:

- Job type (design number or placeholder)
- WBS designation
- Routing sequence by work center
- Labor hours required for the job by work center
- Design tools required for each work center
- Schedule timeframe for the job expressed as a start or need date calculated from the Master Schedule SWBS (Schedule Work Breakdown Structure)

Further, this research assumes the persons who developed the MES utilized many of the industrial engineering principles found in the Handbook of Industrial Engineering by Salvendy (2001). Therefore, this research discusses how information already within a typical MES can be used to support conceptual design decision making, provided the appropriate interface is available, i.e., through the DSS.

7.11.2 Capacity Requirements Planning

In the previous section, two major categories of jobs are listed: 1) jobs being processed and 2) planned future jobs. “Planned future jobs” can be further subdivided within the context of the two major categories. The expansion of item 2) is offered as items a and b in the list that follows:

1) Jobs that are currently being processed
2) Planned future jobs
    a. Firm - jobs based on complete released designs which are planned but have not yet started
    b. Potential - jobs based on incomplete designs which are preliminary planned but have not yet started

The “Planned future jobs – Potential” category based incomplete designs does not appear to be widely utilized and is infrequently discussed in the literature. One example found in the literature (of only a few located) dealt with Intel’s implementation of a next generation MES. (Mouli, 2005.) Though it is fairly common to simulate future work using this approach in large blocks of task hours, it is atypical for individual jobs to be planned in detail prior to design release. The main reason “Planned future jobs – Potential” is not widely utilized is because the detailed work center routing information required is typically unavailable until *after* a design is released. However, the logic presented thus far in the RIM-based DSS mitigates this problem, and therefore, alleviates the constraint and opens the way for a new manufacturing opportunity. “Planned future jobs – Potential” are discussed in Section 7.12. Before discussing “Planned future jobs – Potential” is necessary to first discuss “Planned future jobs – Firm.”

With regard to “Planned future jobs – Firm,” i.e., planned jobs based on complete designs, this research assumes once a complete design is released, a job is planned using the order release logic existing within the Factory Management and Planning activities. (Factory Management and Planning are Activities 4 and 5 on the IDEF0 diagrams in Chapter 2.) Typically, Factory Management Planning releases an order/job. The Planning activity develops the routing (by CBS work center) and associates the job to previously written tool orders, or writes new tool orders. Then, logic within the Factory Management System prices/assigns labor hour requirements using WMS data and Master Schedule SWBS information maintained by Business Management.

A baseline assumption of this research is that some organization/group within the Factory Management activity (typically Industrial Engineering) develops information to describe the maximum available capacity by work center for the current facility configuration. The maximum available capacity is expressed in terms of the labor hours by CBS work center by shift (usually three). In addition, the “Firm Planned Capacity” is typically derived by using a combination of the planned standards hours by CBS work center in conjunction with factors by work center, i.e., historical realization (viz., measured efficiency) and “other” factors. “Other” factors might include additional realization losses due to first article manufacturing of a new product. These factors are typically maintained in a capacity requirements planning (CRP) simulation database within the MES. (Baker and Reckers, 2004; Zaner, 2003.)

Examples of capacity calculations for one work center are provided in Table 7.23. In machining work centers, the labor hours equal the machine hours if one worker is assigned per machine. Otherwise, machine hours are forecasted in a similar manner.

Table 7.23 Capacity Requirements Forecasting Example

		Accounting/Budget Month				
CBS Work Center	Mo	Jan	Feb	Mar	Apr	May
Number	Yr	2008	2008	2008	2008	2008
ABC	M-Days	23	20	20	20	25
Max Headcount		20	20	20	20	20
Maximum Actual Hours Available						
	Shift Hrs	Hours Per Month per Shift				
Shift 1	8	3680	3200	3200	3200	4000
Shift 2	7	3220	2800	2800	2800	3500
Shift 3	6	2760	2400	2400	2400	3000
Forecasted Actual Hours Firm Planned (Complete Designs)						
Standard Hours		1064	925	925	925	1157
Historical Realization		60%	60%	60%	60%	60%
R_F		1.6667	1.6667	1.6667	1.6667	1.6667
Other (TBD)		1.1000	1.1000	1.1000	1.1000	1.1000
Total Factor		2.7667	2.7667	2.7667	2.7667	2.7667
Shift 1 Actual Hours	8	2944	2560	2560	2560	3200
Firm Planned Capacity (Complete Designs)						
Shift 1	8	2944	2560	2560	2560	3200
Shift 2	7	0	0	0	0	0
Shift 3	6	0	0	0	0	0
Available Capacity Remaining						
Shift 1	8	736	640	640	640	800
Shift 2	7	3220	2800	2800	2800	3500
Shift 3	6	2760	2400	2400	2400	3000

Table 7.23 is offered to illustrate how capacity requirements are developed to make decisions related to capacity planning. The table is not intended to represent the only way to make these types of calculations. The purpose of the table is to illustrate that in order to make an assessment of available capacity in a given timeframe, this type of information must be developed and utilized.

The top segment of Table 7.23 contains the M-days (i.e., manufacturing days) per month for a given year and the maximum headcount possible for work center ABC. The next segment illustrates the calculation of the "Maximum Actual Hours Available" based on the headcount and the number of shift hours. (For example, in January 2008, M-days =23, Max Headcount =20, and Shift 1 hours = 8; 23 x 20 x 8 = 3680 hours.)

The third segment of the table depicts how standard hours are adjusted by various factors to develop the "Forecast Actual Hours Firm Planned (Complete Designs)." The "Firm Planned Capacity (Complete Designs" depicts the results of the calculations in the segment just prior. R_f is the realization (i.e., performance or efficiency) factor. R_f is the inverse of "Historical Realization." (For example, a historical realization of 60% converts to an Rf = 1/0.60 = 1.667; 1.667 + 1.1000 = 2.7667. In January 2008, 1064 standard hours have been planned and these standard hours are estimated to require 1064 x 2.7667 = 2944 actual hours charged.)

The last section of Table 7.23 provides the value for "Available Capacity Remaining." The "Available Capacity Remaining" is calculated by subtracting the "Firm Planned Capacity" in a given accounting month from the "Maximum Actual Hours Available." Referring to the last segment of Table 7.23, in the month of January 2008, a second shift is not required, in that, there are 736 forecasted hours of remaining capacity. (3680 available hours – 2944 actual hours forecast = 736 hours remaining.)

If capacity requirements go beyond the "Maximum Actual Available Hours Available" in a given accounting month for the "Shift 1" level, then overtime and/or additional shifts are necessary. If the total forecasted capacity requirement exceeds the level that a three-shift operation can handle, then facility configuration changes are warranted or the work must be planned for outside suppliers. Even though manufacturing should have contingency plans that outline the alternatives for increasing capacity, this type of information is typically not easy to locate. Hence, the DSS will prompt the IPT to make the appropriate inquiries.

It is important to note that "accounting month" is part of capacity and performance records because it forms the baseline for budget and cost calculations accomplished by the Business Management activity. Period-specific rates and factors (See Figure 7.24, page 301) are applied to period-specific requirements in order to determine period-specific costs. *Cost* and *budget* are relative terms and only have real world meaning when in the context of a properly derived timeframe of occurrence, (i.e., schedule.) For example year 1999 dollars are not the same as year 2000 dollars in the context of pricing and contracts. If the labor hours are expended in a different timeframe, then cost will be different. Hence, this type of knowledge has reciprocal interdependencies related to "Sequencing" (See Figure 7.26).

In many instances, the type of capacity information presented Table 7.23 is difficult to extract from a MES. Quite often individuals writes personal ad hoc programs to obtain the information or is in close contact with individuals responsible for capacity requirements planning (CRP) in order to obtain accurate and timely data. This research assumes than an interface is developed which allows information to be directly assessed by the RIM-based DSS for use by the IPT, and thus, eliminates ad hoc approaches.

Conceptual information hierarchies related to the "Planned future jobs – Firm" in the context of CRP are illustrated in Figures 7.27 and 7.28. Figure 7.27 conveys the capacity information discussed in Table 7.23. Figure 7.28 conveys the scheduling hierarchies required to support pricing jobs (i.e., planning work measurement standard hours) over a specified timeframe. It is assumed the information in Figures 7.27 and 7.28 are maintained by industrial engineering in support of the Factory Management activity, (i.e., IDEF0 diagrams, Chapter 2.)

- Capacity
  - Work center number
    - Max headcount by shift
    - Max machines by shift
    - Max actual hours available by shift by accounting month
    - Forecast actual hours firm planned (complete designs) by shift by accounting month
      - Firm planned Capacity (complete designs) by shift by accounting month
      - Available capacity remaining by shift by accounting month
      - Contingency plans
      - TBD
- CRP Simulation
  - Work center
    - Realization factor
      - Other factors
      - TBD

Figure 7.27 Capacity Conceptual Information Hierarchies

- Scheduling
  - SWBS
    - Work center number
      - M-days
  - Historical data
    - Work center makespan (setback)
      - Design selective anticipation features
      - Tool design selective anticipation features (not defined in this research)
      - TBD

Figure 7.28 Scheduling Conceptual Information Hierarchies

7.11.3 IPT Decisions Supported by the DSS

If a working-level IPT has access to information about how much capacity is available by work center in a given timeframe (accounting month), then they can use this information to make decisions about incomplete designs. In particular, the IPT can identify potential bottlenecks.

In addition, if Factory Management has already developed utilized industrial engineering and manufacturing engineering to develop contingency plans related to capacity, then the IPT should not spend their time doing redundant studies/assessments. Instead, the starting point of discussion should be the existing “Contingency plans” in Figure 7.27. A key job of the IPT and the manufacturing representative is to coordinate with Factory Management.

There are several problems in the context of capacity planning that fall within Verganti’s classification of *superficial anticipation.* Many schedule issues uncovered during the detail design phase, (i.e., after the design is released) result from superficial anticipation of capacity requirements during the earlier stages of design. Quite often IPTs do not have industrial engineering expertise and fail to realize the significance of capacity or cannot address relevant capacity issues.

It is one thing to understand what *capacity* generally means, however, it is something else to understand how capacity data are developed, maintained, and used on a daily basis in the Factory Management activity. Similarly, many do not understand the need to do *capacity contingency planning* even when a new design is not fully defined.

The proposed DSS allows IPT members to query a specific timeframe and view existing capacity. Examples of queries include:

- Design Processing Categories (Figure 7.7, page 203),
- CBS work center (Figure 7.4, page 181), and
- total project

Before proceeding to the next section, it is necessary to recap the information development thus far in the context of the RIM-based information hierarchies not yet defined. The previously defined Figure 7.26 now has additional items colored in “black” that have been defined, and areas in “blue italics” that remain to be defined. The “Sequencing decisions based on the management of existing requirements” segment is now black. The updated version is presented in Figure 7.29.

- Design Processing Categories **(Section 7.7)**
    - Product Data Management System (EBOM/Product Structure) **(Section 7.3; 7.8.2)**
        - Features [Features $_{\text{DesignSelectiveAnticipation (Mfg)}}$ + Features $_{\text{ManufacturingSelectiveAnticipation (Design)}}$]
          (Section 6.8.1; Figure 76.8) **(Section 7.9.2)**
            - *Feedforward Planning Model (FFPM)*
                - CBS Work Centers **(Section 7.4.2)**
                    - **#1** Technical processing systems information
                        - M&P standards and specifications by work center **(Section 7.6)**
                        - Equipment inventory **(Section 7.8)**
                            - Equip specs correlated to Features $_{\text{DesignSelectiveAnticipation (Mfg)}}$ + Features $_{\text{ManufacturingSelectiveAnticipation (Design)}}$ + Features$_{\text{DesignOther(Mfg)}}$
                        - Manufacturing Engineering studies by work center **(Section 7.6)**
                        - Specific processing capabilities limits [Features$_{\text{DesignSelectiveAnticipation(Mfg)}}$ Features$_{\text{ManufacturingSelectiveAnticipation(Design)}}$] **(Section 7.9)**
                        - Design specific tooling used on past designs (historical data by product by type, i.e., part of tool classification and control system) **(Section 7.8.2)**
                            - Tool codes (Tool Type; Features $_{\text{DesignSelective anticipation (Mfg)}}$)
                            - Tools to make tools on past designs
                                - Tool features (Will not be addressed)
                        - Non-design specific tools (located in the areas, such as portable hole processing systems) inventory **(Section 7.6)**
                    - **#2** Resources (management strategy) (overhead not discretely considered)
                        - Direct labor hours (touch) **(Section 7.10)**
                        - Machine hours **(Section 7.10)**
                        - Direct labor hours (other) **(Section 7.10)**
                        - Procurement dollars **(Section 7.10)**
                    - **#3** *Sequencing (scheduling/availability)*
                        - Sequence decisions based on the management of existing requirements (already planned for other products) **(Section 7.11)**
                            - Labor hours by shift by timeframe **(Section 7.11)**
                            - Machine hours by shift by timeframe **(Section 7.11)**
                        - *Technical sequencing considerations linked with the Master Schedule (internal scheduling)* **(Section 7.12)**
                        - *Sequencing decisions based on management of new requirements by work center (incomplete designs)* **(Section 7.13)**

Highlighted numbers refer to capability contexts discussed in Section 6.5

Figure 7.29 RIM DSS Development Conceptual Framework (Update of Figure 7.26)

Capacity

- Capacity
  - o Work center number
    - ▪ Max headcount by shift
    - ▪ Max machines by shift
    - ▪ Max actual hours available by shift by accounting month
    - ▪ Forecast actual hours firm planned (complete designs) by shift by accounting month
      - Firm planned Capacity (complete designs) by shift by accounting month
      - Available capacity remaining by shift by accounting month
      - Contingency plans
      - TBD
- CRP Simulation
  - o Work center
    - ▪ Realization factor
      - Other factors
      - TBD

Figure 7.27 Capacity Conceptual Information Hierarchies

Design control number: xxxxxxx – xxx
Processing category: NC Machining
Nomenclature (Detail type): Bulkhead

CBS Work Center #	CBS Processing Description	Design Tools	Make /Buy
TBD	Material receipt -plate(s)		
901	Plate inspection		
802	Vibroengrave		
203	Tooling holes	Tool code	X
101	Plate surface mill		
102	*1 Milling Trial Run	Tool code	X
301	Hand finish - clean		
xxx	------------------------------	--------	-----
200*	*2 Special hole processing	Tool code	X
203	*2 Tooling (coordinated) holes	Tool code	X
xxx	------------------------------	--------	-----
801	Stamp		

Table 7.12 Framework of FFPM Fabrication Plan (Segment only)

Work center schedule (make span)

- Scheduling
  - o SWBS
    - ▪ Work center number
      - M-days
  - o Historical data
    - ▪ Work center makespan (setback)
      - Design selective anticipation features
      - Tool design selective anticipation features (not defined in this research)
      - TBD

Figure 7.28 Scheduling Conceptual Information Hierarchies

CODIFICATION STRATEGIES

Reciprocal interdependencies are managed via relational conceptual information hierarchies queries by:

1) *Information hierarchies (databases)*
2) *FFPM Fabrication Plan*
3) *CBS*

Figure 7.30 Recap of DSS Conceptual RIM-Based Codification Discussed In Section 7.11

7.12 Technical Sequencing Considerations Linked with the Master Schedule

In this section, the segment of Figure 7.29 titled "Technical sequencing considerations linked with the Master Schedule" is discussed. First, feedforward planning concepts from Verganti's study are overviewed within the context of IPTs and sequencing/scheduling decisions. This is followed by the presentation of a high-level, first-article Master Schedule. Next, RIM concepts are used to identify the potential problems with current approaches. Finally, the method selected for the conceptual RIM-based DSS is presented.

7.12.1 Feedforward Planning Concepts and Sequencing (Scheduling)

In Verganti's research, three concepts are identified that reflect on the sequencing (scheduling) aspect of feedforward planning: 1) feedforward planning effectiveness, 2) early process engineering, and 3) superficial anticipation. These concepts are previously discussed in Section 6.10 within the context of "Resources" and can similarly be applied to "Sequencing."

With regard to feedforward planning effectiveness, a 16-year study of DOD acquisition projects performed by Swank et al. (2000) reports the average overrun in cost and schedule were 40% and 62%, respectively. Hence, it is reasonable to conclude current approaches are ineffective in feedforward planning efforts.

Similarly, with regard to early process engineering, there is inadequate knowledge transfer between the earliest decision makers and the working-level IPTs. As discussed in Chapter 5, working-level IPTs are typically required to *start over* and develop new estimates of internal schedules, even though these tasks were supposedly performed as a part of contract negotiations to support development of the Master Schedule.

As discussed in Section 5.1, page 115, initial programmatic schedules and cost estimates are developed using a top-down methodology, which does not lend itself to knowledge transfer for the purposes of managing a project. As soon as the contract is awarded, the working-level IPTs are required to perform a bottoms-up type approach to develop information required to populate management information tools.

Another type of knowledge transfer does not typically take place, which was previously discussed in Chapter 1, and as observed by this author. The decision drivers of downstream activities (e.g., capacity and line balancing) are not transferred to working-level IPT decision makers. (Lee et al., 2001; Ma et al., 2002; Reich et al., 1999; Richards, 2000; Xiong, 2003; Yang et al., 2003.) IPTs tend to develop schedule knowledge in a “vacuum” and fail to recognize the *real schedule* can only be determined by loading the MES with requirements information so consideration of other jobs and line balancing can take place. There is typically no direct link between the MES scheduling logic and the schedules the working-level IPTs develop. As discussed earlier in the context of capacity analysis, unless an IPT member has an industrial engineering background, he/she likely does not understand the concept of line balancing.

With regard to the third feedfoward planning concept, selective anticipation, the problems existing in the context of estimating “resources” requirements also occur within the context of predicting “sequencing/scheduling” requirements. Superficial anticipation results in a basis of information with limited definition from which to make meaningful change or adjustment. Even though the working-level IPTs are provided a high-level schedule, they are tasked to develop a bottoms-up schedule, identify errors, and fill in the technical design and manufacturing details to support a Master Schedule that has already been agreed upon. In order to properly develop the internal schedule, bottoms-up estimates of "resources" requirements are needed in order to develop internal schedules.

As discussed in Chapter 1, many IPT members do not have the expertise to accomplish the required level of detailed work with incomplete design information. This is the result of cultural issues (Asideu and Gu, 1998; Austin et al., 2001; Tolometti and Saunders, 1998; Vollerthun, 1998; Wierda, 1990) and specialized hierarchies of knowledge (Winter, 1999.) This assertion is further supported by this author's practical work experience. Due to the lack of expertise, a superficial baseline of sequencing/scheduling knowledge exists for a very long time on a project. During the early stages of design, *changes* to the baseline become fruitless; detailed trade studies of specific design changes result in *discrete deltas* that are incorporated to a *parametric* baseline.

7.12.2 High-Level Master Scheduling for First-Article

The "Integrated Master Plan and Schedule Guide" published by the Air Force Material Command (2004) provides an example of an initial Integrated Master Schedule (IMS) provided to a working-level IPT. The IMS is often created in *Microsoft Project* and has very high-level activities. Examples of high-level activities include:

- Design drawings
- Manufacturing plan
- Material procurement

- Fabricate in-house parts
- Assemble first article

The IPTs are required to develop internal schedules for these types of high-level activities using the WBS and Master Schedule to support the development of the Schedule Work Breakdown Structure (SWBS) for the first-article. The Master Schedule typically contains the contractual delivery dates that have been promised to the customer and the SWBS contains internal scheduling dates that are required to meet the contractual deliveries.

An example of a first-article internal schedule is provided in Figure 7.31, and it includes only the expanded schedule setbacks (backward schedules) for the forward, center, and aft components of an aircraft. The word setback is a commonly used aircraft term, as an aircraft manufacturing progress is typically conveyed as a combination of setbacks and positions. (Gunston, 1988.) Gantt chart dates coincide with the estimates of when these blocks of tasks start and finish, as well as how the total hours (e.g., resources) are spread in the proposal/bid.

Based on this author's experience, there are typically few resources estimates or technical requirements descriptions traceable to lower-level task accomplishment. (If this were not the case, then the Air Force Material Command document (2004) would not direct working-level IPTs to create this detailed information.) Estimating jargon refers to the situation as a *peanut butter spread*, so from the very beginning the estimate of cost is not reflective of a useful combination of resources and schedule requirements. Though not depicted on the Figure 7.31, an internal schedule also includes typically the projected calendar dates of starts and completions for each WBS.

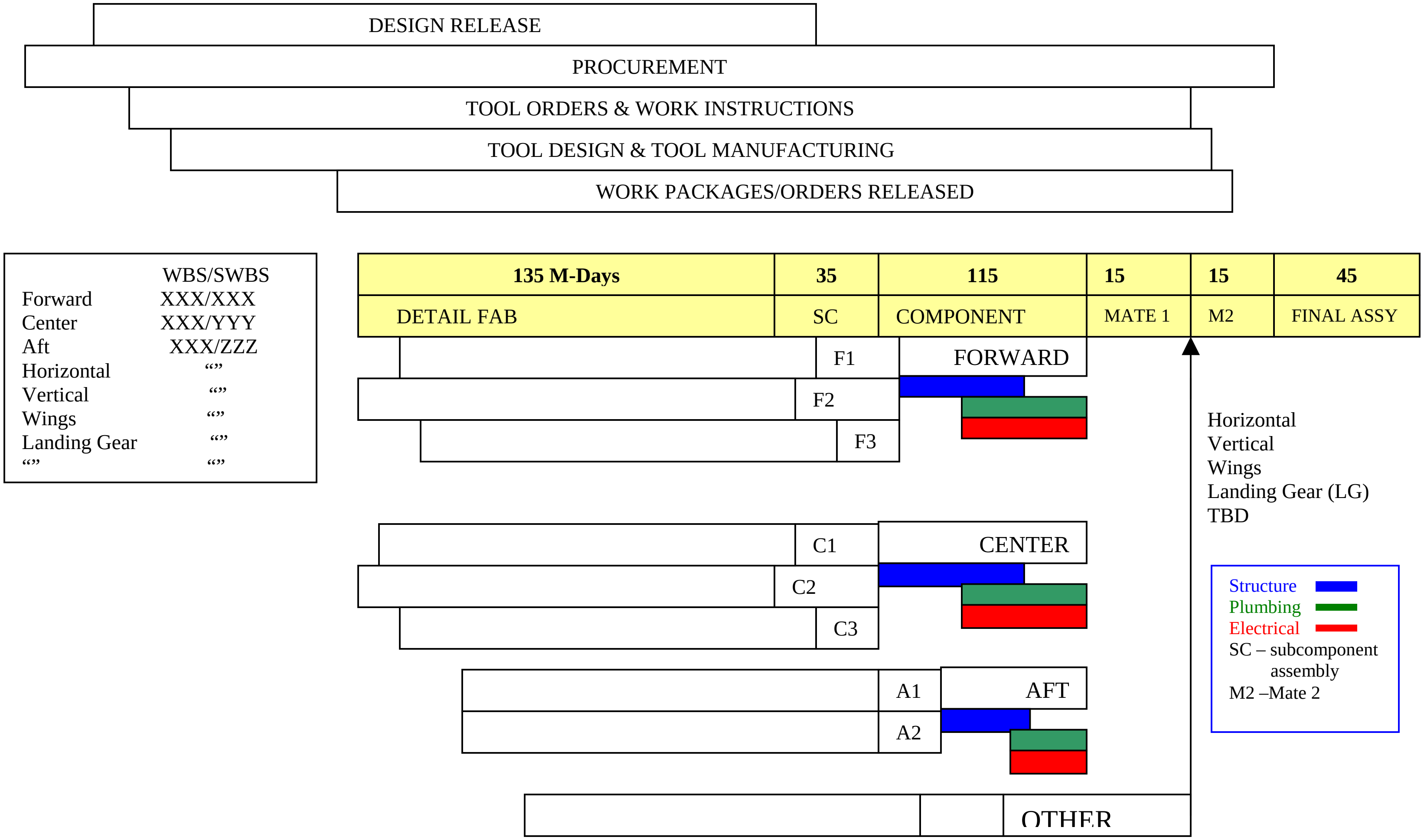


Figure 7.31 Example of a First-Article Internal Schedule Provided to an IPT

Figure 7.31 depicts the typical schedule an IPT is provided. Note the entire design release scheduled span is combined into one bar. Similarly, procurement, and other tasks are represented as large bars only. The job of the IPT is to fill in all of the details to make them match this type of high-level project plan representation.

7.12.3 RIM-Diagram of Sequencing (Scheduling)

In this section, a RIM-diagram (Table 7.24) is used to depict the reciprocal interdependencies existing between various tasks in the context sequencing (scheduling) of requirements. The RIM-diagram highlights some of the issues related to how schedules are created for aircraft manufacturing.

Table 7.24 RIM-Diagram of Sequencing (Master and Internal Scheduling)

Master/Internal Scheduling	COMMON Conceptual	COMMON Conceptual and Preliminary	COMMON Detail First-Article	NEW (In-House) NEW (Suppliers)
TECHNICAL Master Schedule				
Developer	Business Management scheduling and Customer	Business Management scheduling and Customer	Business Management scheduling and Customer	Business Management scheduling and Customer
Information, Tools, and Processes	Customer delivery rate SOW Estimated EBOM Estimated design release curve Estimated hours per aircraft and learning curves Historical data , models, and "best guess"	*Master Schedule delivery dates and total quantities can change based on performance to internal schedules and subsequent negotiations*		ME & IE input -------------------------- Procurement and/or supplier information
Internal Schedules				
Developer	Business Management scheduling	IPTs	Factory Management MES	IPTs ----------------------------- Procurement/suppliers
Information, Tools, and Processes	Same as Master	Start with Master Schedule, IMS, and IMP provided EBOM by WBS and SWBS (Process not well defined)	Scheduling logic within the MES Based on actual order release and need date	Internal-based on promised design release date and the estimated need date (Cost increases when dates change)
Level of Detail		NOT WELL DEFINED		
Engineering Designs	High-level (project)		Design release (DR)	High-level (project) --------------------------
Work Instructions	High-level (project)		Dependent upon DR	In general, high-level, with the exception of critical long lead procurement
Tool Designs	High-level (project)		Dependent upon DR	
Tool Manufacturing	High-level (project)		Dependent upon DR	
Order Release	High-level (project)		Occurs when all preceding tasks are complete (MES) Becomes actual start date	
Procurement	High-level (project) Some suppliers identified		Dependent upon DR and/or related order date	Identify suppliers; quotes and contracts
Fabrication	High-level (WBS)		Discrete by EBOM design number (job) and work center Completion dates of prior tasks become actual start date	New equipment and processes – vendors located; technology insertion plan developed
Assembly	High-level (WBS)		Discrete by EBOM design number (job) and work center station	
RESOURCES				
Fabrication Hours	High-level (WBS)		Detailed- work center	
Assembly Hours	High-level (WBS)		Detailed-station	
Direct Labor (non-touch)	High-level (WBS)		Detailed-WBS/CBS	
Procurement Dollars	High-level (WBS)		Detailed-WBS/CBS	
SEQUENCING				
Assembly line balancing	Assumed		MES capacity leveling Load sequencing and crew loading Cost increases when disconnects occur	Supplier delivery dates must be synced with in-house need dates Cost increases when disconnects occur
Fabrication line balancing	Assumed			

IPTs should utilize information from detail design sytems, i.e., MES

The RIM-diagram in Table 7.24 is organized in a similar manner to prior RIM diagrams. Various designations of *Common* and *New* are found within the column headings, and major categories of *Technical, Resources, and Sequencing* are located in the far left column. The *Common* information is further segmented into three columns related to design phase, while the *New* information is broken into in-house and suppliers considerations using by dividing the cell into upper and lower segments.

In the following paragraphs, Table 6.24 is discussed. Note that every cell in the table is not discussed; but instead only a major sampling is offered. The significant point being highlighted is information exchange processes and procedures between the working-level IPTs and upstream and downstream users of information are not well defined.

The first section under “Technical” is labeled “Master Schedule.” The Master Schedule is developed based on negotiations between Business Management and the customer. The contractual Master Schedule is typically composed of aircraft deliveries only, i.e., the internal schedules for each aircraft are left to the discretion of the enterprise and can be somewhat flexible.

The second section under “Technical” is titled “Internal Schedules.” The initial internal schedules are developed by Business Management at a very high-level and only designate major milestones and blocks of tasks. The IPTs are expected to fill in all of the details below the high-level tasks for internal scheduling. Once an actual order is released to initial the scheduling of a specific job at the work center level, the Factory Management MES schedules an order based on the actual order release date and the need date specified in the job/order. Suppliers develop their own internal schedules during negotiations with the enterprise. Typically, these are based on promised dates of important information. If these dates are missed, then costs increase.

The third subsection under "Internal Schedules" is titled "Level of Detail." The Integrated Master Schedule (IMS) and the Integrated Master Plan (IMP) (AFMC, 2004) contain elements at a very high-level for "Engineering Designs, Work Instructions, Tool Designs, Tool Manufacturing, Order Release, etc." Business Management initially agrees to "High-level (project)" schedules. Subsequently, the working-level IPTs are supposed to fill in the lower-level details; however a method for doing so is not well defined. Once the Engineering activity achieves a "Design release (DR)," the task details are determined using information with detail design phase systems located in Factory Management, Planning, and Tooling activities (i.e., IDEF0 diagrams, Chapter 2). The actual internal schedules are developed by MES logic at order release.

The fourth subsection under "Internal Schedules" is labeled "Procurement." Scheduling procured items is a significant task and greatly impacts the total cost of an aircraft. Approximately 46.7% of the cost of an aircraft is based on direct material (Kloos, 2007). The master scheduling process typically identifies some suppliers for long lead items, but many suppliers will have to be identified by the IPTs.

The fifth subsection under "Internal Schedules" has two categories, "Fabrication" and "Assembly." During the initial pricing of a project, the schedule is defined at a high-level based on the WBS, i.e., "High-level (WBS)." The working-level IPTs are not involved in the sequencing/scheduling process until after the post-award conference. (AFMC, 2004.) Ultimately, designs are scheduled using design numbers from the

EBOM, and these design numbers correspond to jobs manufactured as design detail parts or *kits* of parts.

The next section of the RIM-diagram is titled “Resources.” The subsections are designated as “Fabrication Hours, Assembly Hours, Direct Labor (non-touch), and Procurement Dollars.” (Procurement is mentioned a second time in this section to emphasize the spreading of procurement dollars over a given timeframe, and how the scheduling of these dollars affects cost calculations.) During conceptual design, the resources are scheduled at a high-level, and during the detail design phase, the resources are scheduled at a detailed level. A significant point being highlighted is that information exchange processes and procedures between the working-level IPTs and both upstream and downstream users of information are not well defined.

The next section of the RIM-diagram is titled “Sequencing.” The subsections are designated as “Assembly line balancing” and “Fabrication line balancing.” During the conceptual design phase, requirements are scheduled at a high-level and a balanced line is assumed. During the detail design phase, requirements are scheduled within the MES and line balancing is accomplished via the MES. Again, the lack of well-defined information exchange processes and procedures is highlighted .

Based on this author’s experience, line balancing of assembly hours for an aircraft is typically more difficult than fabrication. The CBS work centers used in Detail Fabrication rarely change significantly from aircraft to aircraft. However, the assembly task typically requires the designation of a new work area of the facility and the creation of several new assembly work centers.

In addition, in order to balance the *total* assembly line (i.e., both Fabrication and Assembly simultaneously), the assembly installation sequence, (i.e., *load sequence*) processing sequence, and personnel assignments (i.e., *crewloads*) are required for each assembly task by EBOM control number. Similarly, even though estimates of design tooling are made early on, the real estimates of production rate tooling (i.e., tooling required to sustain a monthly rate of production) cannot be accomplished until the line balancing activity is complete. Until a real allocation of hours is established, it is very difficult to determine the amount of work that can be accomplished on one or more aircraft concurrently. Parallel work is typically required to meet the contractual Master Schedule delivery dates/rates. (The enterprise does not complete build one aircraft before starting another. Instead, multiple equivalent aircraft are in work concurrently in any given month.)

In the next section, the approach selected for the conceptual DSS is discussed.

7.12.4 Technical Scheduling Considerations: Conceptual DSS Approach

Based on the information from the RIM-diagramming effort in Table 7.23, the approach selected for the conceptual DSS requires several conceptual information hierarchies, as well as a new type of design release, a formal *concept design release*. A formal *concept design release* provides the missing link between the baseline product data in the EBOM and the scheduling systems used by the enterprise. This missing link is required for similar reasons to the FFPM fabrication plan in Table 7.12, page 217.

The typical MES already has the capability to schedule jobs for the purposes of simulation, i.e., “Planned future jobs - Potential.” The use of a concept design release makes the simulation capability of the MES more useful to working-level IPT decision making. Further, the use of a concept design release allows the utilization of material requirements planning (MRP) systems to schedule procured items and link them to the MES, where appropriate.

Recall from Section 7.11, the MES can typically handle two major categories of jobs are listed, 1) Jobs being processed, and 2) Planned future jobs. “Planned future jobs” is further divided into “a. Firm” and “b. Potential” and the two major categories are thus organized as follows:

1) Jobs that are currently being processed

2) Planned future jobs
    a. Firm - Jobs based on complete designs (final release)
    b. Potential - based on incomplete designs

As discussed previously in Section 7.11, the “Planned potential jobs” function is not widely utilized because of the details required to make its use feasible. However, since the RIM-based conceptual DSS utilizes a FFPM fabrication plan, which includes a routing sequence and tooling requirements, in addition calculating work measurement standard values, the use of MES simulation capability becomes more feasible.

The use of a more formal conceptual design release procedure provides additional structure for a more defined baseline and addresses issues related to superficial anticipation. A formal conceptual design release potentially provides a clear baseline from which to compare conceptual design assumptions to the actual resulting detail design in order to facilitate enterprise learning. The main obstacle to using a formal concept design release is likely cultural for reasons similar to those discussed in relation to the use of work measurement in Section 7.8.10 related to work measurement.

A conceptual design release is formalized by a *conceptual design release package* of electronic information. Previously defined conceptual information hierarchies combined with IPT decisions made within the framework of the DSS support the generation of this package as follows:

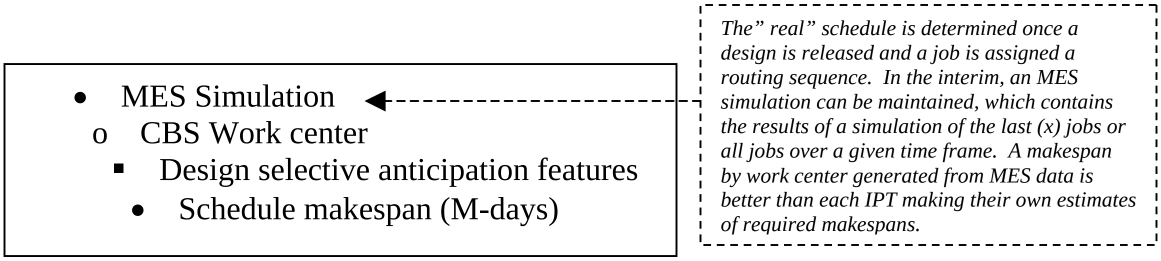
- PDMS information hierarchies correlating WBS and design selective anticipation features
- IPTs select “design processing category”
- DSS correlates “design selective anticipation features” to ME Technical information hierarchies to obtain the beginning FFPM fabrication plan
- IPTs finalize FFPM fabrication plan, which includes (routing sequence by work center CBS and tooling requirements)
- Once the package is released,
    - MES work measurement system grouped standard “price” the design selective anticipation features (labor requirements) by CBS work center
    - MES scheduling system “load” the calculated standard values by CBS in the appropriate timeframe utilizing the Business Management SWBS

Formal concept design releases are not widely discussed in the literature, and only one example could be located. Zhang et al. (2004) utilizes a concept design release in the development of a collaborative product development tool for Qiqihaer Railway Ltd. Company, a railway manufacturer in China. The use of a concept design release facilitated the integration of information by enabling the use of software tools to work at a lower-level of detail earlier in the design process. The information gained by digital documentation of the conceptual design is envisioned to be used in future virtual prototyping modeling and simulation.

Even if an aircraft manufacturing enterprise adopts a formal concept design release process, the requirement to emulate sequencing/scheduling logic within the MES remains to support the envisioned framework of the RIM-based DSS until the point in the process where the *conceptual design release package* is released.

The conceptual information hierarchies required for simulation of the MES prior to an actual release of some type (whether the *conceptual design* release package or the finalized *detail design* release package) are provided in Figure 7.32. It is assumed the information in Figure 7.32 is developed and maintained by industrial engineering.

Until an order is released and a job planned at the work center level, one can only simulate the schedule the MES will ultimately assign. An MES simulation involves running program to determine the average make span by work center being assigned in a specified time frame. For example, the MES simulation can be an average schedule make span for all jobs in a month. When estimating the potential make span, the MES simulation value is used until an actual release is made.



- MES Simulation
  - o CBS Work center
    - ▪ Design selective anticipation features
      - Schedule makespan (M-days)

The" real" schedule is determined once a design is released and a job is assigned a routing sequence. In the interim, an MES simulation can be maintained, which contains the results of a simulation of the last (x) jobs or all jobs over a given time frame. A makespan by work center generated from MES data is better than each IPT making their own estimates of required makespans.

Figure 7.32 Conceptual Information Hierarchies to Support MES Simulation of CBS Work Center Internal Schedule Makespan (or Setback)

Another aspect of "Internal Schedules" in Table 7.23 involves the "Direct Labor (non-touch)" and "Procurement Dollars." These internal schedules are required in order to link the CBS work center schedules to the IPT deliverables schedules (i.e., detail designs, work instructions, design tools), as well as to generate total cost calculations.

In Chapter 5, the working-level IPT members for this research are defined as:

- Structural design engineer (leader) (direct labor-design deliverable)
- Systems design engineer (direct labor-design deliverable)
- Test engineer (direct labor-design deliverable)
- Tool designer (direct labor-tool design deliverable)
- Planner (direct labor-work instructions deliverable)
- Manufacturing engineer (direct labor-tooling integration deliverable)
- Manufacturing representative (allocated to touch labor as supervision)
- Purchasing representative (allocated to direct material)
- Cost representatives (various; depends on program management) (overhead)
- Quality assurance representative (allocated as direct overhead)

Chapter 5 discusses important working-level IPT decisions, include determining:

- The number of deliverables their respective activities (i.e., IDEF0 diagram activities, Chapter 2) are responsible for producing

- Schedule makespan (i.e., M-days) required for each deliverable, (i.e., released designs, work instructions, tool designs, tool orders, etc.)

- Precedence relations between deliverable tasks

- The design release date that supports the contractual Master Schedule aircraft delivery date

In order for the envisioned RIM-based DSS to support the listed working-level IPT decisions, logic rules must exist within the DSS, and schedule makespan templates must exist within conceptual information hierarchies that pertain to sequencing/scheduling information for each task. In addition, the information must be relatable to the FFPM fabrication plan in Table 7.12, page 217.

Table 7.12 illustrates the fabrication plan for one detail design and it lists the requirements for four design tools by tool code and by CBS work center. For the purposes of illustration, it is assumed that two of the listed design tools are in-house *make* tools, two are *buy* tools, and one of the in-house make tools requires a tool for its manufacture (a *tool-to-make-tool*.) Based on these assumptions, the following deliverables can be projected using the conceptual information hierarchies in Figure 7.33 and internal DSS logic rules illustrated in parentheses:

- Detail designs – 1 *(based on 1 NC machined bulkhead)*
- Detail work instructions – 1 *(based on 1 per detail design)*
- Tool orders – 5 *(based on 2 make, 2 buy, 1 make tool-to-make-tool)*
- Tooling work instructions – (based on 2 + 1 = 3 *(2 make, 1 make tool-to-make-tool)*
- Tool models – 5 (electronic data) *(based on 2 make, 2 buy, 1 make tool-to-*
- *make-tool)*
- Tool designs – 2+1 = 3 *(based on 2 make, 1 make tool-to-make- tool)*

Figure 7.33 reflects an update to the previously presented Figure 7.23 (page 299), and includes DSS operation-required sequencing/scheduling information. The conceptual information hierarchies' updates are color coded in blue italics. It is assumed the design templates information is developed and maintained by analysts in the Engineering activity and tool code templates information is developed and maintained by industrial engineering.

- Project
  - Design selective anticipation features
    - Detail design templates
      - Design hours
      - *Design M-days*
      - Work instructions hours
      - *Work instructions M-days*
    - Tool code templates
      - Tool model hours
      - *Tool model M-days*
      - Tool design hours
      - *Tool design M-days*
      - Tool manufacturing work instructions hours
      - *Tool manufacturing work instructions M-days*

Figure 7.33 Non-Recurring Engineering and Tool Design Direct Labor and Scheduling Conceptual Information Hierarchies (Updated Figure 7.23)

If a raw material, design processing category, or tool code is designated as a procured (i.e., buy), then the DSS requires temporary values for the estimated procurement timeframes. These temporary values are used for working-level IPT decision making until the procurement representative obtains rough order of magnitude (ROM) quotes or final bids for each identified requirement.

Project templates for these types of schedules are viewed as additions to previously presented “Procurement Management” conceptual information hierarchies in Figure 7.23, page 299, and are required for DSS operation to support IPT decision making needs. The news conceptual hierarchies are provided in Figure 7.34 and updates are color coded in blue italics. It is assumed the procurement historical data information is developed and maintained by the procurement section of the Business Management activity.

- Raw Material
  - M&P material code
    - Plate
      - Standard sizes
        - Vendors
          - Cost (BY, unburdened $)
          - Order history (M-days)
          - *Order history (M-days)*
        - Project templates
          - Project x
          - Cost (BY, unburdened $)
          - *Order history (M-days)*
    - Bar stock
      - Same as plate
        - “”
    - TBD
      - Same as plate
        - “”
    - Tool Code
      - Where used
        - Design selective anticipation features
          - Standardized ranges
            - Vendors (historical data)
              - Cost (BY, unburdened $)
              - *Order history (M-days)*
            - Project templates
              - Project x
              - Cost (BY, unburdened $)
              - *Order history (M-days)*
  - ROM Quotes
    - Design number
    - Tool number
    - TBD
  - Final Bids
    - Design number
    - Tool number
    - TBD
  - TBD

Figure 7.34 Procurement Management Conceptual Information Hierarchies
(Update of Figure 7.23 Reflecting Scheduling Templates)

7.12.5 Integrated Resources Scheduling System

An integrated resources schedule system (IRSS) is required to accomplish sequencing/scheduling of resources that are not managed by the MES. It is assumed working-level IPTs have access to an IRSS, which organizes project management type information at the project and enterprise level. This type of information is required to assist with project management decision making within the respective IPT supported Activities, (i.e., IDEF0 diagrams' Activities, Chapter 2.) It is assumed the Business Management activity coordinates the development and maintenance of an IRRS, and the system is interfaced to the DSS.

For example, as discussed in Chapter 5, page 115, a planner representing the Planning activity (i.e., IDEF0 diagram, Figure 2.6, page 55) typically does not develop all tool orders or work instructions. Instead, he/she develops – or coordinates - *the plan* for how the tool orders and work instructions are managed. An example of the type of information in a conceptual IRSS to support working-level IPT decision making is provided in Table 7.25.

Table 7.25 Example of Integrated Resources Scheduling Information

DESIGN CONTROL NUMBER xxxxxx-xxx

			DOLLARS	HRS	NEED	START	FINISH
BUSINESS MAGAGEMENT	(Activity #1)						
Master Scheduling							
SWBS					00/00/00		
Procurement							
Raw material	xx		TBD		00/00/00		
ENGINEERING	(Activity #3)						
Design				TBD		00/00/00	00/00/00
Release date							00/00/00
PLANNING	(Activity #5)						
Total tool orders		5					
Work instructions (WI)							
Tool manufacturing WI	2			TBD		00/00/00	00/00/00
Design manufacturing WI	1			TBD		00/00/00	00/00/00
Total WI		3					
TOOLING	(Activity #6)						
Tool Models							
T1	1			TBD		00/00/00	00/00/00
T2	1			TBD		00/00/00	00/00/00
T3	1			TBD		00/00/00	00/00/00
T4	1			TBD		00/00/00	00/00/00
T5	1			TBD		00/00/00	00/00/00
Total tool models		5					
Tool Designs	2						
(Tool-to-make-tool) T3	1			TBD		00/00/00	00/00/00
T4	1			TBD		00/00/00	00/00/00
T5	1			TBD		00/00/00	00/00/00
Total tool designs		5					
Procured Tools							
T1	1		TBD		00/00/00		
T2	1		TBD		00/00/00		
Total procured tools		2					
Manufactured Tools							
(Tool-to-make-tool) T3	1		TBD	TBD		00/00/00	00/00/00
T4	1		TBD	TBD		00/00/00	00/00/00
T5	1		TBD	TBD		00/00/00	00/00/00
Total in-house manufactured tools		3					
FABRICATION	(Activity #7)						
Tool manufacturing			Not detailed in this research			00/00/00	00/00/00
Design manufacturing			TBD	TBD		00/00/00	00/00/00
Design completion							00/00/00

(Factory Management Activities #2 and #4 are not correlated to monitored IPT deliverables)

Table 7.25 is organized to associate to the FFPM fabrication plan in Table 7.12, page 217, and the DSS logic illustrated on page 332. The Chapter 2 IDEF0 activities are denoted on the table, along with corresponding IPT deliverables. The table is assumed to be nearly self-explanatory, and therefore, not specifically discussed. The dates shown in Figure 7.24 are based a backward scheduling approach beginning with the contractual delivery date of an aircraft. (Watson et al., 1997.)

Table 7.25 provides the reader with an even greater understanding of the amount of detailed information working-level IPTs are required to develop in order to facilitate the operation of various computerized systems within the enterprise. Even though other disciplines may be the *owners* of these systems - and actually have representatives performing data entry and reporting functions - the IPTs are typically required to generate the underlying values and/or knowledge. The previously presented templates in Figure 7.32 , Figure 7.33, and Figure 7.34 support these efforts.

7.12.6 Recap of DSS Development Thus Far

Before moving on to the next section, it is necessary to recap the information development thus far in the context of the RIM-based capability framework. Previously presented Figure 7.29 is updated to become Figure 7.35. Figure 7.35 has additional items colored in black that are defined in Section 7.11 and areas coded in blue italics that remain to be defined.

- Design Processing Categories **(Section 7.7)**
  - Product Data Management System (EBOM/Product Structure) **(Section 7.3; 7.8.2)**
    - Features [Features $_{\text{DesignSelectiveAnticipation (Mfg)}}$ + Features $_{\text{ManufacturingSelectiveAnticipation (Design)}}$]
      (Section 7.8.1; Figure 7.8) **(Section 7.9.2)**
- *Feedforward Planning Model (FFPM)*
  - CBS Work Centers **(Section 7.4.2)**
    - **#1** Technical processing systems information
      - M&P standards and specifications by work center **(Section 7.6)**
      - Equipment inventory **(Section 7.8)**
        - Equip specs correlated to Features $_{\text{DesignSelectiveAnticipation (Mfg)}}$ + Features $_{\text{ManufacturingSelectiveAnticipation (Design)}}$ + Features$_{\text{DesignOther(Mfg)}}$
      - Manufacturing Engineering studies by work center **(Section 7.6)**
      - Specific processing capabilities limits [Features$_{\text{DesignSelectiveAnticipation(Mfg)}}$ Features$_{\text{ManufacturingSelectiveAnticipation(Design)}}$] **(Section 7.9)**
      - Design specific tooling used on past designs (historical data by product by type, i.e., part of tool classification and control system) **(Section 7.8.2)**
        - Tool codes (Tool Type; Features $_{\text{DesignSelective anticipation (Mfg)}}$)
        - Tools to make tools on past designs
          - Tool features (Will not be addressed)
      - Non-design specific tools (located in the areas, such as portable hole processing systems) inventory **(Section 7.6)**
    - **#2** Resources (management strategy) (overhead not discretely considered)
      - Direct labor hours (touch) **(Section 7.10)**
      - Machine hours **(Section 7.10)**
      - Direct labor hours (other) **(Section 7.10)**
      - Procurement dollars **(Section 7.10)**
    - **#3** *Sequencing (scheduling/availability)*
      - Sequence decisions based on the management of existing requirements (already planned for other products) **(Section 7.11)**
        - Labor hours by shift by timeframe **(Section 7.11)**
        - Machine hours by shift by timeframe **(Section 7.11)**
      - Technical sequencing considerations linked with the Master Schedule (internal scheduling) **(Section 7.12)**
      - *Sequencing decisions based on management of new requirements by work center (incomplete designs)* **(Section 7.13)**

Highlighted numbers refer to capability contexts discussed in Section 6.5

Figure 7.35 RIM DSS Development Capability Conceptual Framework
(Update of Figure 7.29)

It is important to summarize the conceptual RIM-based codification of information hierarchies discussed in Section 7.11 before continuing to Section 7.12. Codification involves the systematic classification and storage of knowledge relationships to address predefined questions/issues. The relationships discussed in Section 7.11 are offered in Figure 7.36. "Sequencing decisions based on management of new requirements by work center" is discussed in the next section, Section 7.13.

- Raw Material
  - M&P material code
    - Plate
      - Standard sizes
        - Vendors
          - Cost (BY, unburdened $)
          - Order history (M-days)
          - *Order history (M-days)*
        - Project templates
          - Project x
          - Cost (BY, unburdened $)
          - *Order history (M-days)*
    - Bar stock
      - Same as plate
        - “”
    - TBD
      - Same as plate
        - “”
    - Tool Code
      - Where used
        - Design selective anticipation features
          - Standardized ranges
            - Vendors (historical data)
              - Cost (BY, unburdened $)
              - *Order history (M-days)*
            - Project templates
              - Project x
              - Cost (BY, unburdened $)
              - *Order history (M-days)*
  - ROM Quotes
    - Design number
    - Tool number
    - TBD
  - Final Bids
    - Design number
    - Tool number
    - TBD
  - TBD

Figure 7.34 Procurement Management Conceptual Information Hierarchies (Update of Figure 7.23 Reflecting Scheduling Templates

WMS CERs – Work Measurement System Cost Estimating Relationships based on feature-based grouped standard values applied at the work center level

Design control number: xxxxxxx – xxx
Processing category: NC Machining
Nomenclature (Detail type): Bulkhead

CBS Work Center #	CBS Processing Description	Design Tools	Make /Buy	Hours Section 7.10	M-days Makespan Section 7.12
TBD	Material receipt -plate(s)			WMS CERs	MES Simulation
901	Plate inspection			WMS CERs	MES Simulation
802	Vibroengrave			WMS CERs	MES Simulation
203	Tooling holes	Tool code	X	WMS CERs	MES Simulation
101	Plate surface mill			WMS CERs	MES Simulation
102	*1 Milling Trial Run	Tool code	X	WMS CERs	MES Simulation
301	Hand finish - clean			WMS CERs	MES Simulation
xxx	-------------------------------	--------	-----	WMS CERs	MES Simulation
200*	*2 Special hole processing	Tool code	X	WMS CERs	MES Simulation
203	*2 Tooling (coordinated) holes	Tool code	X	WMS CERs	MES Simulation
xxx	-------------------------------	--------	-----	WMS CERs	MES Simulation
801	Stamp			WMS CERs	MES Simulation

Table 7.12 (Segment only)

Detail designs	1
Detail work instructions	1
Tool orders	5
Tooling work instructions	3
Tool models	5
Tool designs	3

Relationships on page 296

- MES Simulation
  - CBS Work center
    - Design selective anticipation features
      - Schedule makespan (M-days)

Figure 7.32 Conceptual Information Hierarchies to Support MES Simulation of CBS Work Center Internal Schedule Makespan (or Setback)

Initial estimates of makespan are replaced by refined estimates once the conceptual design is released to the MES for line balancing

- Project
  - Design selective anticipation features
    - Detail design templates
      - Design hours
      - *Design M-days*
      - Work instructions hours
      - *Work instructions M-days*
    - Tool code templates
      - Tool model hours
      - *Tool model M-days*
      - Tool design hours
      - *Tool design M-days*
      - Tool manufacturing work instructions hours
      - *Tool manufacturing work instructions M-days*

Page 296

Non-touch direct labor hours and task M-day spans

Figure 7.33 Non-Recurring Engineering and Tool Design Direct Labor and Scheduling Conceptual Information Hierarchies (Updated Figure 7.23)

<u>CODIFICATION STRATEGIES</u>

Reciprocal interdependencies are managed via relational conceptual information hierarchies queries by:

1) *Information hierarchies (databases)*
2) *FFPM Fabrication Plan*
3) *CBS work center number*

Figure 7.36 Recap of DSS Conceptual RIM-Based Codification Discussed In Section 7.12

7.13 Sequencing Based on Management of "New" Requirements (Incomplete Designs) by Work Center

In this section, the last segment of Figure 7.29 is discussed, i.e., "Sequencing decisions based on management of new requirements." More specifically, scheduling-related IPT decision making in the context of capacity line balancing for conceptual designs (i.e., incomplete designs or designs which are yet to be finalized.)

In Section 7.12.4, the idea of a *conceptual design release package* is presented. Assuming this proposed change is implemented by the enterprise, the IPTs potential for considering line balancing decisions earlier in the product development process is potentially enhanced greatly. Typical line balancing adjustments include scheduling overtime, utilizing additional shifts, rescheduling jobs to lower the direct labor hours requirements in a specific timeframe, and outsourcing task hours.

Once a *conceptual design release package* is released for a design, the MES is enabled to assist with enterprise-level scheduling adjustments in support of factory line balancing. Obviously, the usefulness of this approach is greatly enhanced once a significant total number of packages are released for an aircraft. Further, once the factory line is balanced, it significantly improves the enterprise's ability to balance the entire *direct hours line* (as opposed to just direct touch labor on the assembly line) by connecting the MES information to the Integrated Resource Scheduling System (IRSS) in Section 7.12.5. Once these two information sources are linked, the IPT has complete *start to finish* visibility for project management of deliverables – beginning at the start of the design and ending with fabrication of the design.

Wynn et al. (2005) presents the results of a six-month study conducted by Massachusetts Institute of Technology to identify the root causes of poor performance in defense acquisition programs. Poor scheduling capability and the inability to appropriately breakdown and sequence lower-level tasks was identified as a significant contributor to poor performance.

Based on this author's experience, Wynn's assertions are valid. Current line balancing efforts are typically ineffective because much needed lower-level details at the CBS work center level are not established until much later - when the finalized design is released during the detail design phase. Too often, when a design is released and the real schedule is determined, it is too late for the IPT to proactively address bottlenecks and disconnects. These bottlenecks lead to countless, multiple occurrence of the enterprise waiting for a bottleneck to be corrected so throughput can continue, much in the same manner as Goldratt and Cox (1992) describe in The Goal.

Previously in Section 6.11, jobs within the MES are classified as follows:

1) Jobs currently being processed
2) Planned future jobs
    a. Firm - jobs based on complete released designs which are planned but have not yet started
    b. Potential - jobs based on incomplete designs which are preliminary planned but have not yet started

Additionally in Section 7.11, "Planned future jobs – Firm," i.e., planned jobs based on complete designs is illustrated as Table 7.23 which is repeated here as Table 7.26. In Table 7.26, the capacity requirements by accounting month for a hypothetical work center are offered.

Table 7.26 Example of Capacity Requirements Forecasting for "Planned Future Jobs – Firm"

		Accounting/Budget Month				
CBS Work Center Number	Mo Yr	Jan 2008	Feb 2008	Mar 2008	Apr 2008	May 2008
ABC	M-Days	23	20	20	20	25
Max Headcount		20	20	20	20	20
Maximum Actual Hours Available						
	Shift Hrs	Hours Per Month Per Shift				
Shift 1	8	3680	3200	3200	3200	4000
Shift 2	7	3220	2800	2800	2800	3500
Shift 3	6	2760	2400	2400	2400	3000
Forecasted Actual Hours Firm Planned (Complete Designs)						
Standard Hours		1064	925	925	925	1157
Historical Realization		60%	60%	60%	60%	60%
R_F		1.6667	1.6667	1.6667	1.6667	1.6667
Other (TBD)		1.1000	1.1000	1.1000	1.1000	1.1000
Total Factor		2.7667	2.7667	2.7667	2.7667	2.7667
Shift 1 Actual Hours	8	2944	2560	2560	2560	3200
Firm Planned Capacity (Complete Designs)						
Shift 1	8	2944	2560	2560	2560	3200
Shift 2	7	0	0	0	0	0
Shift 3	6	0	0	0	0	0
Available Capacity Remaining						
Shift 1	8	736	640	640	640	800
Shift 2	7	3220	2800	2800	2800	3500
Shift 3	6	2760	2400	2400	2400	3000

Note Table 7.26 does not contain forecasts of capacity for "Planned Future Jobs – Potential," i.e., jobs based on incomplete/conceptual designs. Once *conceptual design release packages* are released to the MES, the hours required to process these jobs reduces the available capacity remaining. Per Table 7.27, beginning in February 2008, the one-shift capacity is exceeded and a second shift (or overtime) is required.

Table 7.27 Example of Capacity Requirements Forecasting for
“Planned Future Jobs – Firm” and “Planned Future Jobs – Potential”

		Accounting/Budget Month				
CBS Work Center	Mo	Jan	Feb	Mar	Apr	May
Number	Yr	2008	2008	2008	2008	2008
ABC	M-Days	23	20	20	20	25
Max Headcount		20	20	20	20	20
Maximum Actual Hours Available						
	Shift Hrs	Hours Per Month Per Shift				
Shift 1	8	3680	3200	3200	3200	4000
Shift 2	7	3220	2800	2800	2800	3500
Shift 3	6	2760	2400	2400	2400	3000
Forecasted Actual Hours Firm Planned (Complete Designs)						
Standard Hours		1064	925	925	925	1157
Historical Realization		60%	60%	60%	60%	60%
R_F (Realization Factor)		1.6667	1.6667	1.6667	1.6667	1.6667
Other (TBD)		1.1	1.1	1.1	1.1	1.1
Total Factor		2.7667	2.7667	2.7667	2.7667	2.7667
Shift 1 Actual Hours	8	2944	2560	2560	2560	3200
FIRM Planned Capacity (Complete Designs)						
Shift 1	8	2944	2560	2560	2560	3200
Shift 2	7	0	0	0	0	0
Shift 3	6	0	0	0	0	0
POTENTIAL Planned Capacity (Incomplete Designs)						
Shift 1	8	400	640	640	640	800
Shift 2	7	0	700	700	700	875
Shift 3	6	0	0	0	0	0
AVAILABLE Capacity Remaining						
Shift 1	8	336	**0**	**0**	**0**	**0**
Shift 2	7	3220	2100	2100	2100	2625
Shift 3	6	2760	2400	2400	2400	300

If the enterprise does not implement the idea of a *conceptual design release package (CDRP)*, then it does not diminish from the other types of IPT decision making support facilitated by the envisioned RIM-based DSS. However, it does diminish the overall feedforward effectiveness potential and the enterprise's ability to learn by development (i.e., as definedi in Chapter 6.) However, once the FFPM fabrication plan (i.e., Table 7.12 page 217) is available – which is a major component of a conceptual design release package – the idea of a CDRP is the next logical step.

It is now appropriate to update information development thus far in the context of the RIM-based capability framework. Previously presented Figure 7.35 is updated to become Figure 7.37. There are no remaining items left to describe, and the Feedforward Planning Model is complete.

- Design Processing Categories **(Section 7.7)**
  - Product Data Management System (EBOM/Product Structure) **(Section 7.3; 7.8.2)**
    - Features [Features $_{\text{DesignSelectiveAnticipation (Mfg)}}$ + Features $_{\text{ManufacturingSelectiveAnticipation (Design)}}$] **(Section 6.8.1; Figure 7.8)** **(Section 7.9.2)**
      - Feedforward Planning Model (FFPM)
        - CBS Work Centers **(Section 7.4.2)**
          - **#1** Technical processing systems information
            - M&P standards and specifications by work center **(Section 7.6)**
            - Equipment inventory **(Section 7.8)**
              - Equip specs correlated to Features $_{\text{DesignSelectiveAnticipation (Mfg)}}$ + Features $_{\text{ManufacturingSelectiveAnticipation (Design)}}$ + Features$_{\text{DesignOther(Mfg)}}$
            - Manufacturing Engineering studies by work center **(Section 7.6)**
            - Specific processing capabilities limits [Features$_{\text{DesignSelectiveAnticipation(Mfg)}}$ Features$_{\text{ManufacturingSelectiveAnticipation(Design)}}$] **(Section 7.9)**
            - Design specific tooling used on past designs (historical data by product by type, i.e., part of tool classification and control system) **(Section 6.8.2)**
              - Tool codes (Tool Type; Features $_{\text{DesignSelective anticipation (Mfg)}}$)
              - Tools to make tools on past designs
                - Tool features (Will not be addressed)
            - Non-design specific tools (located in the areas, such as portable hole processing systems) inventory **(Section 7.6)**
          - **#2** Resources (management strategy) (overhead not discretely considered)
            - Direct labor hours (touch) **(Section 7.10)**
            - Machine hours **(Section 7.10)**
            - Direct labor hours (other) **(Section 7.10)**
            - Procurement dollars **(Section 7.10)**
          - **#3** Sequencing (scheduling/availability)
            - Sequence decisions based on the management of existing requirements (already planned for other products) **(Section 7.11)**
              - Labor hours by shift by timeframe **(Section 7.11)**
              - Machine hours by shift by timeframe **(Section 7.11)**
            - Technical sequencing considerations linked with the Master Schedule (internal scheduling) **(Section 7.12)**
            - Sequencing decisions based on management of new requirements by work center (incomplete designs) **(Section 7.13)**

Highlighted numbers refer to capability contexts discussed in Section 6.5

Figure 7.37 RIM DSS Development Capability Conceptual Framework (Update of Figure 7.35)

There are no additional conceptual information hierarchies per se presented in this section. A baseline assumption of this DSS conceptual framework is that existing MES logic is capable of handling capacity requirements related to incomplete designs – provided the following information is available: 1) a FFPM fabrication plan (i.e., Table 7.12, page 217) and 2) a conceptual design release package. The FFPM is completed by the IPT within the DSS environment and the conceptual design release package contains the full compliment of information to generate a “Planned Future Jobs – Potential” requirement within the MES. The primary consideration with regard to codification and IPT decision making is the development of an interface, which will extract capacity requirements planning (CRP) information from the MES in a useful format once the “Planned Future job” has been released and planned/loaded.

7.14 Executive Summary of Chapter 7

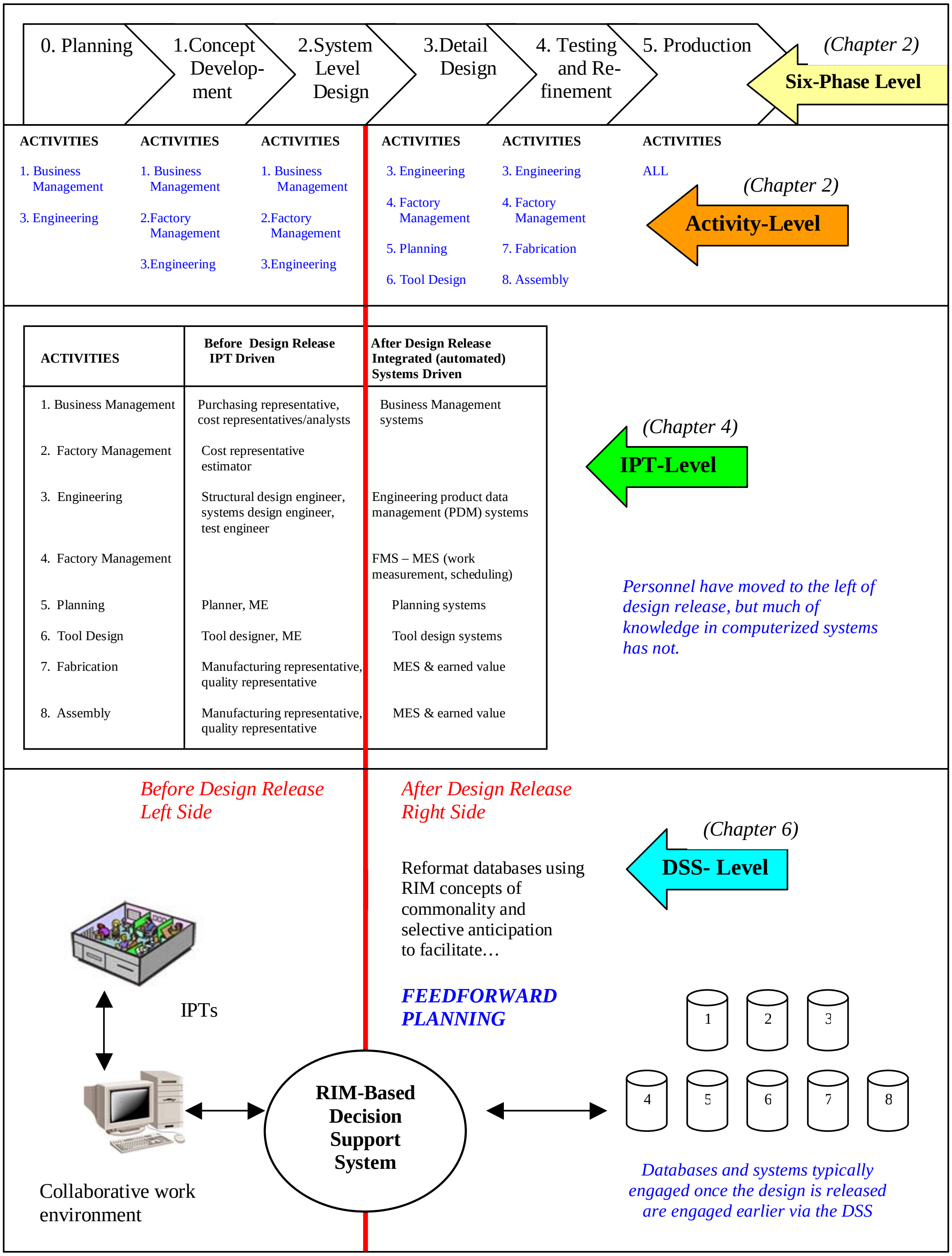
In Chapter 7, Verganti’s findings and concepts are discussed in the context of improving IPT decision making and a conceptual framework for developing a RIM-based DSS is offered. A conceptual framework is a formal way of thinking (i.e., conceptualizing) about a process or system under study, and it represents a coherent set of ideas and concepts organized in a manner that makes them easy to communicate to others. (Wartik, 2007.) This presentation of Chapter 7 material addresses the specific research objectives found in Chapter 1, i.e., objectives 1 and 2c, page 36.

As presented in Chapter 1 page 3, Verganti reports task complexities surrounding the identification of reciprocal interdependencies - and the use of feedforward planning efforts to manage them - is usually hindered by a lack of well-structured methods and the amounts of information required. Chapter 7 offers insights into the complexities of knowledge exchange involved in IPT decision making, and it offers a structured approach to organizing and considering information in the context of reciprocal interdependencies. It is not suggested the methodology presented in Chapter 7 is the only way to consider the exchange of knowledge involved in decision making; but instead, it is a practical, comprehensive way to organize the task complexities of conceptual design decision making for a working-level IPT.

Chapter 7 utilizes RIM-diagramming and accompanying discussion of RIM concepts (i.e., feedforward planning, commonality, selective anticipation, etc.) to characterize the complex interactions and knowledge exchanges involved in working-level IPT decision making. Further, Verganti's factors affecting measurement of successful feedforward planning (i.e., superficial anticipation, early process engineering, preplanning knowledge, and feedforward planning effectiveness) are methodically overviewed. In addition, RIM-diagramming is systematically utilized to identify information constraints and opportunities typically not considered in an organized fashion until after design release.

Design features are defined (e.g., design selective anticipation features, manufacturing selective anticipation features, etc.) and the definitions are subsequently utilized within various conceptual hierarchies supporting IPT decision making – providing a formalized approach for knowledge exchange (and reuse) between the activities on the IDEF0 diagrams (i.e., Chapter 2, pages 53 –56). The most significant improvements to knowledge exchange include the new links established between the systems that support the activities that predominantly occur *before design release* and that occur *after design release*.

By considering the information needs of the IPT members and the information availability during conceptual design in the context of design selective anticipation features and manufacturing selective anticipation features -- changes in typical enterprise information hierarchies are identified to facilitate information exchange in an automated fashion during early conceptual design. Design and manufacturing information that is either unavailable until after design release - or disorganized and not understood by typical IPT members - is made available at a point earlier in the process in support of IPT decision making. Recall Figure 5.2 is presented again as Figure 7.38.



0. Planning	1.Concept Develop-ment	2.System Level Design	3.Detail Design	4. Testing and Re-finement	5. Production
ACTIVITIES	ACTIVITIES	ACTIVITIES	ACTIVITIES	ACTIVITIES	ACTIVITIES
1. Business Management 3. Engineering	1. Business Management 2.Factory Management 3.Engineering	1. Business Management 2.Factory Management 3.Engineering	3. Engineering 4. Factory Management 5. Planning 6. Tool Design	3. Engineering 4. Factory Management 7. Fabrication 8. Assembly	ALL

ACTIVITIES	Before Design Release IPT Driven	After Design Release Integrated (automated) Systems Driven
1. Business Management	Purchasing representative, cost representatives/analysts	Business Management systems
2. Factory Management	Cost representative estimator	
3. Engineering	Structural design engineer, systems design engineer, test engineer	Engineering product data management (PDM) systems
4. Factory Management		FMS – MES (work measurement, scheduling)
5. Planning	Planner, ME	Planning systems
6. Tool Design	Tool designer, ME	Tool design systems
7. Fabrication	Manufacturing representative, quality representative	MES & earned value
8. Assembly	Manufacturing representative, quality representative	MES & earned value

Personnel have moved to the left of design release, but much of knowledge in computerized systems has not.

Reformat databases using RIM concepts of commonality and selective anticipation to facilitate…

Databases and systems typically engaged once the design is released are engaged earlier via the DSS

Figure 7.38 Product Development Process Six-Phase Approach With Activity-Level IPT-Level and DSS Level Modifications

The IPT-level segment of Figure 7.38 illustrates that many concurrent engineering efforts have moved IPT members to the left side of the design release event; but much of the information housed in integrated, computerized systems has not transitioned. In the DSS-level segment of the figure, the RIM-based DSS facilitates the restructuring and reuse of information by utilizing RIM concepts of feedforward planning, commonality, and selective anticipation, coupled with consistent definitions of *design selective anticipation features* and *manufacturing selective anticipation features* to systematically develop, maintain, and exchange common knowledge throughout the enterprise.

More discussion of Chapter 7 efforts and results are offered in Chapter 9, Conclusions and Future Work.

The next chapter, Chapter 8, other approaches are compared to the RIM-based DSS offered in Chapters 6 and 7.

CHAPTER VIII

COMPARISONS OF CONCEPTUAL RIM-BASED DSS APPROACH TO OTHER CONCEPTUAL DESIGN DECISION-MAKING SUPPORT TOOLS AND METHODOLOGIES

One of the primary objectives of this research is to examine the usefulness of RIM concepts in the construction of enterprise systems to support IPT decision making by comparing the RIM-based methodology (i.e., an enterprise manufacturing *capability* framework) and resulting conceptual DSS to other conceptual approaches, frameworks, systems discussed in the literature. This research defines a conceptual manufacturing capability framework using NC machining as the specific case by systematically formalizing enterprise information using reciprocal interdependencies management (RIM) concepts (i.e., feedforward planning, commonality, selective anticipation, etc.)

In Chapter 1, Verganti (1997) acknowledges task complexities involved in the identification of reciprocal interdependencies (RIs) and the use of feedforward planning efforts to manage RIs is usually hindered by a lack of well-structured methods and the amounts of information involved. Although the level of detail in Chapter 6 may be seen as excruciating by some, or even unnecessary by others, it realistically portrays the task complexities involved with IPT knowledge exchange during the early stages of design in the identification of manufacturing constraints and opportunities. Further, it demonstrates a structured approach (i.e., the capability framework and RIM-diagramming) that Verganti and this author have found to be lacking in the literature.

In order to better understand the usefulness of the proposed approach, it is helpful to compare it to a sampling of other concepts and tools found in the literature. These comparisons highlight the contribution this research makes to the body of knowledge.

In order to accomplish the comparison task, the following steps are performed:

- Develop a qualitative assessment tool to rate each approach based on eight factors: inputs, re-creation of results, processes and costs, scheduling, tooling, planning (work instructions), manufacturability, project management, and information reuse
- Select a sample of ten relevant approaches from published research previously discussed in Chapter 3 (i.e., the literature review.)
- Apply a qualitative assessment tool to the ten samples and evaluate the results
- Develop and present conclusions based on the results.

The remainder of Chapter 8 documents the details of the tasks outlined above.

8.1 Qualitative Assessment Tool Development

When performing the literature review, each approach was summarized and notes taken on aspects considered desirable and those that detracted from usefulness in the context of IPT decision making during conceptual design. The desirable attributes were those this research strived to emulate, and the detractors became a list of things to try and improve upon or avoid. Over time, recurring themes came to the forefront and these were grouped into eight categories. The eight categories of the qualitative assessment tool are:

1) Inputs/Entries
2) Regeneration of results
3) Processes and costs
4) Scheduling
5) Tooling
6) Planning (work instructions)
7) Manufacturability
8) Project management and information reuse

The rationale behind the eight categories is offered in the sections that follow. In addition, a discussion of the number and structuring of questions is presented.

8.1.1 Inputs/Entries (Category 1)

The *inputs/entries* category relates to input data/information requirements for a particular approach or system, and whether the information requirements matches the information availability and/or capabilities of an IPT during conceptual design. Topics considered include whether the approach requires a(n):

- *Electronic interface to the design?* If so, then the approach is not useful with sketches.
- *Nearly complete design?* If so, then the approach is not as useful during conceptual design because design information is sketchy.
- *Process plan (routing sequence) from another source?* If so, then the approach is not considered to be as worthwhile as an approach having internal logic to generate a routing sequence.
- *Specialist/expert user?* For example, the system requires a lot of entries that the average IPT member may not know or be reasonably expected to estimate. If so, then the approach is not considered as useful as one that could be utilized by an average user.
- *User to stipulate the required manufacturing tasks?* If so, then the approach is not considered as useful as one that offers feedback related manufacturing tasks/requirements to the IPT/user based on the design requirements.

- *User to develop his/her own categories of "features?"* Similarly, does the approach adequately define "feature" and provide sufficient examples? If so, these types of approaches are not considered as useful as those defining features for the user.

8.1.2 Regeneration of Results (Category 2)

The *regeneration of results* category relates to how easily a reader can regenerate the results from the information presented in the literature. In addition, the category also refers to how much of the underlying logic of the approach is applicable to a new conceptual design decision making problem.

- *Is the data and underlying logic presented in such a way that the reader can recreate the results?* If not, then the approach is not considered as useful. (A recurring problem is that software prototype demonstration values could not be associated with the equations presented in the text.)

- *Are the production rules, sequencing logic, and cost calculation logic presented in a manner that would facilitate the reader creating a working prototype?* If not, then the approach is not considered as useful. (A recurring problem with the literature is conceptual approaches lack critical explanation of the underlying logic and/or methodology. Instead, significant tasks are relegated to a single figure on a high-level diagram.

8.1.3 Processes and Costs (Category 3)

The *processes and costs* category relates to the elements of *total cost* presented and whether critical components of cost that IPT members typically are interested in are discernable among the defined total. In addition, the category also refers to the amount of underlying logic presented in an approach that can be applied to a new problem.

- *Are all the processes required to complete a NC machined design addressed?* If not, then the approach only deals with the shaping/milling portion of the NC fabrication processing and fails to recognize other processes required to complete a NC machined design.

- *Are design tooling requirements/costs (tool design or tool manufacturing) discussed?* If not, then the approach fails to acknowledge a major portion of design cost that often determines whether one process is selected over another process, or how tolerances often lead to additional tooling costs.

- *Are planning costs associated with work instructions discussed, even if not discretely addressed?* If not, then the approach fails to acknowledge a significant contributor to first article cost.

- *Is the timing of expenditures discussed?* If not, then the approach fails to acknowledge the significance of the time value of money. If a cost value is going to be used in discussions with the customer or make comparisons for vendor selection, it cannot be a "relative cost" that has limited application usefulness in the context of managing real work or making real comparisons.

- *Is overhead cost applied based on design characteristics or categories?* If not, then the approach treats all overhead cost the same, and potentially understates NC machining cost.

- *Are learning factors considered?* If not, then the approach fails to recognize that first article products are treated differently in real world cost evaluations.

8.1.4 Scheduling (Category 4)

The *scheduling* category relates to the elements of scheduling tasks in conjunction with cost calculations that are a critical element of IPT decision making. Scheduling information needs considered include: 1) task durations to perform capacity analysis, 2) a timeframe of occurrence for financial considerations, or 3) task sequencing decisions relative to precedence relationships. Questions addressed in the assessment tool include:

- *Are scheduling considerations discussed as part of the approach?* If not, then the approach fails to recognize the importance of scheduling with regard to project management and cost related IPT decision-making.
    - Critical path items may require that a decision be based on schedule as opposed to "single item cost" because of the implications to total enterprise cost expenditures.

- Make span is required to do capacity analysis.

- Make span is required to schedule associated tasks, such as tool design, tool manufacturing, and assembly.

- Make span is necessary to load enterprise systems that utilize timing of expenditures for overhead cost, escalation, and budgetary considerations.

- Personnel requirements should be considered in conjunction with the task being accomplished so that appropriate personnel forecasting can be accomplished.

8.1.5 Tooling (Category 5)

The *tooling* category relates to the information needs associated with IPT decision making in the context of establishing design tooling requirements and costs. Questions addressed by the qualitative assessment tool include:

- *Are tooling and/or fixtures considered?* If not, then the approach is not as useful to an IPT as an approach recognizing the need to specifically address tooling requirements. An approach receives a non-negative assessment for mentioning tooling cost, but to receive a positive assessment requires some aspect of cost be driven by the explicit consideration of tooling.

- *Are discrete tooling requirements considered?* If not, then the approach is not considered as useful as an approach that links design requirements to tooling requirements.

8.1.6 Planning (Category 6)

The *planning* category relates to routing and work instructions tasks considered in the approach. For example, whether work instructions or a routing sequence is required to facilitate the approach. In addition, another consideration is whether work instructions tasks are considered as an integral part IPT tasks/deliverables and the overall project plan.

- *Are planning (work instructions) tasks considered?* If not, this approach is not as highly rated as an approach that recognizes the need for process sequencing and the consideration of work instructions tasks in the IPT's project plan for completing a design.

8.1.7 Manufacturability (Category 7)

Many approaches discuss the importance of considering *manufacturability*, but typically do not provide sufficient detail with regard to the methodology to accomplish this goal. In addition, published works often lack relevant examples of how their envisioned approach works in the context of a real world decision. Too often, the tasks and complexities involved in considering manufacturability are oversimplified so that the approach presented seems more worthwhile, (i.e., oversimplify the problem in order to make a uncomplicated solution applicable.)

- *Does the approach consider manufacturability verification?* If not, the approach would not be considered as useful to IPT decision making.
- *Are production rules used as part of design verification?* If not, the approach is considered less useful to IPTs and receives a lower rating.
- *Are manufacturability examples provided for key processes?* If not, then the approach is not considered as useful as one that provides examples of designs, production rules, and design features relationships to multiple processes.

8.1.8 Project Management and Reuse (Category 8)

The project management and reuse category relates to whether the need to manage a task within the scheme of existing enterprise decision making systems is acknowledged and whether information reuse is supported within the approach. Too often, approaches are stand-alone demonstrations of software packages, and the need to integrate the approach to other enterprise activities knowledge and systems (so it does not become other than another island of information) is not addressed.

- *Does the approach recognize the need to reuse information on similar products and decisions?* If not, the approach is not considered to be as useful as one recognizing the importance of this reuse consideration.

- *Does the approach recognize the need to link the information to other activities, users, or systems?* If not, this approach is not considered as pertinent to IPT decision making as one that recognizes the need to exchange information.

- *Is pertinent requirements (or cost) data generated in a format useable, without change, into other enterprise systems?* If not, the approach is not considered as useful as one which avoids ad hoc data exchange.

- *Is the output from a system in a format which facilitates capacity analysis without additional data manipulations?* If not, the approach is not considered as useful to IPTs for project planning purposes.

8.1.9 Number of Questions and Structure of the Qualitative Assessment Tool

The qualitative assessment tool is divided into eight categories, and contains a total of 26 questions/statements that are answered yes (Y), no (N), or maybe (M). All questions/statements are formatted so that a positive response is “Yes.” Further, all 26 questions are answered “Yes” for the conceptual RIM-based DSS presented by this research.

The formatting of the questions is not meant to imply the conceptual RIM-based DSS is the *end all* of research in this area. Since this is a qualitative assessment tool, an easy mechanism for comparison had to be developed using the conceptual RIM-based DSS as the baseline. Having a mixture of yes and no answers would make comparisons difficult, while comparisons to a "Yes" baseline is easier to understand. An example of the qualitative assessment tool is found in Table 8.1.

Table 8.1 Qualitative Assessment Tool

	R-Research #S-Sample	R	#S	#S	#S
Q	Category 1: Inputs				
1	Approach does not require an interface to a conceptual design file	Yes			
2	Approach does not require a nearly complete drawing	Yes			
3	Approach does not require a nearly complete process plan	Yes			
4	Approach does not require a specialist user	Yes			
5	Approach does not require user to make assumptions on manufacturing tasks	Yes			
6	Approach does not require user to categorize part features	Yes			
	Category 2: Regeneration of Results				
7	The logic and underlying data used by the approach is presented in a manner that can be recreated by the reader	Yes			
8	Underlying production rules, sequencing logic, and cost information is presented in a manner that would facilitate the creation of a working system	Yes			
	Category 3: Processes and Costs				
9	All major processes required to complete a machined part are addressed	Yes			
10	Manufacturing cost addressed	Yes			
11	Tooling cost specifically addressed	Yes			
12	Planning cost specifically addressed	Yes			
13	Timing of expenditures is considered (time value of money)	Yes			
14	Overhead is not applied discretely based on part characteristics	Yes			
15	Learning factors were considered	Yes			
	Category 4: Scheduling				
16	Approach includes scheduling considerations	Yes			
	Category 5: Tooling				
17	Tooling and/or fixturing is considered	Yes			
18	Discrete tooling requirements are considered	Yes			
	Category 6: Planning				
19	Planning tasks (work instructions/routing) are part of the approach	Yes			
	Category 7: Manufacturability				
20	Approach includes manufacturability verification	Yes			
21	Production rules used by manufacturing are part of design verification	Yes			
22	Manufacturability examples are provided for key processes	Yes			
	Category 8: Project Management and Information Reuse				
23	Approach recognizes the need to reuse information from similar products	Yes			
24	Approach links data to the systems of downstream users/activities	Yes			
25	The cost data could be rolled into other financial forecasting systems	Yes			
26	Output would allow for capacity analysis	Yes			
	Total Yes Answers	26			
	Total Maybe Answers	0			
	Total No Answers	0			

8.2 Selection of Comparative Approach Samples From Published Works

Ten published works were selected from the research discussed in the literature review. The works were chosen because, in this author's option, they exemplified some of the better approaches with regard to one or more facets potentially supporting IPT conceptual design decision making. The comparative approaches selected are listed in Table 8.2 by year of publication, with the most recent publication being first.

Table 8.2 Comparative Approach Samples

No.	Author(s)	Title	Source
1	Shehab and Abdalla (2001)	An Integrated Prototype System for Cost Effective Design	Concurrent Engineering Research and Applications, 9, 4, 243-256.
2	Tseng and Jiang (2000)	Evaluating Multiple Feature-Based Machining Methods Using an Activity-Based Cost Analysis Model	International Journal of Advanced Manufacturing Technology, 16, 617-623.
3	Wei and Egbelu (2000)	A Framework for Estimating Manufacturing Cost from Geometric Design Data	International Journal of Computer Integrated Manufacturing, 13,1, 50-63.
4	Feng and Zhang (1999)	Conceptual Process Planning: A Definition and Functional Decomposition	Manufacturing Engineering Divisions, ASME, Manufacturing Science and Engineering, 10, 97-106.
5	Shing (1999)	Design for Manufacture of a Cost-Based System for Molded Parts	Advances in Polymer Technology, 18,10, 33-42.
6	Evans et. al (1998)	Manufacturing Process Flow Simulation: An Economic Analysis Tool	30th International SAMPE Technical Conference, October 20-24, 589-595.
7	Ou-Yang and Lin (1997)	Developing an Integrated Framework for Feature-Based Early Manufacturing Cost Estimation	International Journal of Advanced Manufacturing Technology, 13, 618-629.
8	Ong (1995)	Manufacturing Cost Estimation for PCB Assembly: An Activity-Based Approach	International Journal of Production Economics, 38, 159-172.
9	Khoshnevis et. al (1994)	A Cost Based System for Concurrent Part and Process Design	Engineering Economist, 40, 1, 101-124.
10	Park and Khoshnevis (1993)	A Real-Time Computer-Aided Process Planning System as a Support Tool for Economic Product Design	Journal of Manufacturing Systems, 12, 2, 181-192.

The primary goal of using the qualitative assessment tool is o provide insights into the RIM-based DSS an improvement over a selection of other approaches, (i.e., methodologies, frameworks, or systems) available in the literature.

8.3 Qualitative Assessment Tool Results

The results of the qualitative assessment tool are presented in a series of tables found on the pages that follow. First, the detailed assessments for each of the ten samples are provided in Tables 8.3 – 8.6, followed by an executive summary, Table 8.7.

Table 8.3 Qualitative Assessment Tool Results for Samples 1 Through 3

	R-Research #S-Sample	R	#1	#2	#3
Q	Category 1: Inputs				
1	Approach does not require an interface to a conceptual design file	Yes	M	N	N
2	Approach does not require a nearly complete drawing	Yes	M	Y	N
3	Approach does not require a nearly complete process plan	Yes	Y	Y	Y
4	Approach does not require a specialist user	Yes	Y	Y	M
5	Approach does not require user to make assumptions on manufacturing tasks	Yes	Y	Y	N
6	Approach does not require user to categorize part features	Yes	Y	Y	Y
	Category 2: Regeneration of Results				
7	The logic and underlying data used by the approach is presented in a manner that can be recreated by the reader	Yes	N	Y	N
8	Underlying production rules, sequencing logic, and cost information is Presented in a manner that would facilitate the creation of a working system	Yes	N	N	N
	Category 3: Processes and Costs				
9	All major processes required to complete a machined part are addressed	Yes	N	N	N
10	Manufacturing cost addressed	Yes	Y	Y	Y
11	Tooling cost specifically addressed	Yes	N	N	N
12	Planning cost specifically addressed	Yes	N	N	N
13	Timing of expenditures is considered (time value of money)	Yes	N	N	N
14	Overhead is not applied discretely based on part characteristics	Yes	Y	N	N
15	Learning factors were considered	Yes	N	M	N
	Category 4: Scheduling				
16	Approach includes scheduling considerations	Yes	N	N	N
	Category 5: Tooling				
17	Tooling and/or fixturing is considered	Yes	Y	Y	Y
18	Discrete tooling requirements are considered	Yes	N	N	N
	Category 6: Planning				
19	Planning tasks (work instructions/routing) are part of the approach	Yes	N	N	N
	Category 7: Manufacturability				
20	Approach includes manufacturability verification	Yes	Y	N	Y
21	Production rules used by manufacturing are part of design verification	Yes	Y	N	N
22	Manufacturability examples are provided for key processes	Yes	N	N	N
	Category 8: Project Management and Information Reuse				
23	Approach recognizes the need to reuse information from similar products	Yes	N	N	N
24	Approach links data to the systems of downstream users/activities	Yes	N	N	N
25	The cost data could be rolled into other financial forecasting systems	Yes	N	N	N
26	Output would allow for capacity analysis	Yes	N	N	N
	Total Yes Answers	26	9	8	5
	Total Maybe Answers	0	2	1	1
	Total No Answers	0	15	17	20

Table 8.4 Qualitative Assessment Tool Results for Samples 4 Through 6

	R-Research #S-Sample	R	#4	#5	#6
Q	Category 1: Inputs				
1	Approach does not require an interface to a conceptual design file	Yes	N	Y	Y
2	Approach does not require a nearly complete drawing	Yes	N	Y	Y
3	Approach does not require a nearly complete process plan	Yes	Y	Y	Y
4	Approach does not require a specialist user	Yes	M	Y	Y
5	Approach does not require user to make assumptions on manufacturing tasks	Yes	Y	Y	Y
6	Approach does not require user to categorize part features	Yes	N	Y	Y
	Category 2: Regeneration of Results				
7	The logic and underlying data used by the approach is presented in a manner that can be recreated by the reader	Yes	N	Y	N
8	Underlying production rules, sequencing logic, and cost information is presented in a manner that would facilitate the creation of a working system	Yes	N	N	N
	Category 3: Processes and Costs				
9	All major processes required to complete a machined part are addressed	Yes	N	Y	Y
10	Manufacturing cost addressed	Yes	Y	Y	Y
11	Tooling cost specifically addressed	Yes	N	Y	Y
12	Planning cost specifically addressed	Yes	N	N	N
13	Timing of expenditures is considered (time value of money)	Yes	N	Y	Y
14	Overhead is not applied discretely based on part characteristics	Yes	Y	Y	Y
15	Learning factors were considered	Yes	N	N	N
	Category 4: Scheduling				
16	Approach includes scheduling considerations	Yes	N	Y	Y
	Category 5: Tooling				
17	Tooling and/or fixturing is considered	Yes	Y	Y	Y
18	Discrete tooling requirements are considered	Yes	N	M	Y
	Category 6: Planning				
19	Planning tasks (work instructions/routing) are part of the approach	Yes	N	N	M
	Category 7: Manufacturability				
20	Approach includes manufacturability verification	Yes	Y	Y	Y
21	Production rules used by manufacturing are part of design verification	Yes	Y	Y	Y
22	Manufacturability examples are provided for key processes	Yes	N	Y	N
	Category 8: Project Management and Information Reuse				
23	Approach recognizes the need to reuse information from similar products	Yes	N	N	Y
24	Approach links data to the systems of downstream users/activities	Yes	N	N	Y
25	The cost data could be rolled into other financial forecasting systems	Yes	N	M	M
26	Output would allow for capacity analysis	Yes	N	M	Y
	Total Yes Answers	26	7	17	19
	Total Maybe Answers	0	1	3	2
	Total No Answers	0	18	6	5

Table 8.5 Qualitative Assessment Tool Results for Samples 7 Through 9

	R-Research #S-Sample	R	#7	#8	#9
Q	Category 1: Inputs				
1	Approach does not require an interface to a conceptual design file	Yes	N	Y	M
2	Approach does not require a nearly complete drawing	Yes	N	Y	M
3	Approach does not require a nearly complete process plan	Yes	Y	Y	Y
4	Approach does not require a specialist user	Yes	Y	Y	Y
5	Approach does not require user to make assumptions on manufacturing tasks	Yes	Y	Y	Y
6	Approach does not require user to categorize part features	Yes	Y	Y	Y
	Category 2: Regeneration of Results				
7	The logic and underlying data used by the approach is presented in a manner that can be recreated by the reader	Yes	Y	N	N
8	Underlying production rules, sequencing logic, and cost information is presented in a manner that would facilitate the creation of a working system	Yes	N	N	N
	Category 3: Processes and Costs				
9	All major processes required to complete a machined part are addressed	Yes	N	Y	N
10	Manufacturing cost addressed	Yes	Y	Y	Y
11	Tooling cost specifically addressed	Yes	N	M	N
12	Planning cost specifically addressed	Yes	N	N	N
13	Timing of expenditures is considered (time value of money)	Yes	N	N	N
14	Overhead is not applied discretely based on part characteristics	Yes	Y	Y	N
15	Learning factors were considered	Yes	N	N	N
	Category 4: Scheduling				
16	Approach includes scheduling considerations	Yes	N	N	N
	Category 5: Tooling				
17	Tooling and/or fixturing is considered	Yes	Y	Y	Y
18	Discrete tooling requirements are considered	Yes	N	N	N
	Category 6: Planning				
19	Planning tasks (work instructions/routing) are part of the approach	Yes	N	N	N
	Category 7: Manufacturability				
20	Approach includes manufacturability verification	Yes	Y	Y	M
21	Production rules used by manufacturing are part of design verification	Yes	Y	Y	M
22	Manufacturability examples are provided for key processes	Yes	N	N	N
	Category 8: Project Management and Information Reuse				
23	Approach recognizes the need to reuse information from similar products	Yes	Y	Y	N
24	Approach links data to the systems of downstream users/activities	Yes	N	N	N
25	The cost data could be rolled into other financial forecasting systems	Yes	N	N	N
26	Output would allow for capacity analysis	Yes	N	N	N
	Total Yes Answers	26	11	13	6
	Total Maybe Answers	0	0	1	4
	Total No Answers	0	15	12	16

Table 8.6 Qualitative Assessment Tool Results for Sample 10

	R-Research #S-Sample	R	#10		
Q	Category 1: Inputs				
1	Approach does not require an interface to a conceptual design file	Yes	Y		
2	Approach does not require a nearly complete drawing	Yes	Y		
3	Approach does not require a nearly complete process plan	Yes	Y		
4	Approach does not require a specialist user	Yes	Y		
5	Approach does not require user to make assumptions on manufacturing tasks	Yes	Y		
6	Approach does not require user to categorize part features	Yes	Y		
	Category 2: Regeneration of Results				
7	The logic and underlying data used by the approach is presented in a manner that can be recreated by the reader	Yes	N		
8	Underlying production rules, sequencing logic, and cost information is presented in a manner that would facilitate the creation of a working system	Yes	N		
	Category 3: Processes and Costs				
9	All major processes required to complete a machined part are addressed	Yes	Y		
10	Manufacturing cost addressed	Yes	Y		
11	Tooling cost specifically addressed	Yes	Y		
12	Planning cost specifically addressed	Yes	N		
13	Timing of expenditures is considered (time value of money)	Yes	N		
14	Overhead is not applied discretely based on part characteristics	Yes	Y		
15	Learning factors were considered	Yes	N		
	Category 4: Scheduling				
16	Approach includes scheduling considerations	Yes	N		
	Category 5: Tooling				
17	Tooling and/or fixturing is considered	Yes	Y		
18	Discrete tooling requirements are considered	Yes	M		
	Category 6: Planning				
19	Planning tasks (work instructions/routing) are part of the approach	Yes	N		
	Category 7: Manufacturability				
20	Approach includes manufacturability verification	Yes	Y		
21	Production rules used by manufacturing are part of design verification	Yes	Y		
22	Manufacturability examples are provided for key processes	Yes	N		
	Category 8: Project Management and Information Reuse				
23	Approach recognizes the need to reuse information from similar products	Yes	Y		
24	Approach links data to the systems of downstream users/activities	Yes	M		
25	The cost data could be rolled into other financial forecasting systems	Yes	M		
26	Output would allow for capacity analysis	Yes	M		
	Total Yes Answers	26	14		
	Total Maybe Answers	0	4		
	Total No Answers	0	8		

Table 8.7 provides the ranking of each sample based on "Yes" responses, and Table 8.8 provides the percentages of positive results by question.

Table 8.7 Ranking of Results Based on "YES" Responses

#S	Author(s)	Article Title	Yes	Maybe	No
6	Evans et al. (1998)	Manufacturing Process Flow Simulation: An Economic Analysis Tool	19	2	5
5	Shing (1999)	Design for Manufacture of a Cost-Based System for Molded Parts	17	3	6
10	Park and Khoshnevis (1993)	A Real-Time Computer-Aided Process Planning System as a Support Tool for Economic Product Design	14	4	8
8	Ong (1995)	Manufacturing Cost Estimation for PCB Assembly: An Activity-Based Approach	13	1	12
7	Ou-Yang and Lin (1997)	Developing an Integrated Framework for Feature-Based Early Manufacturing Cost Estimation	11	0	15
1	Shehab and Abdalla (2001)	An Integrated Prototype System for Cost Effective Design	9	2	15
2	Tseng and Jiang (2000)	Evaluating Multiple Feature-Based Machining Methods Using an Activity-Based Cost Analysis Model	8	1	17
4	Feng and Zhang (1999)	Conceptual Process Planning: A Definition and Functional Decomposition	7	1	18
9	Khoshnevis et al. (1994)	A Cost Based System for Concurrent Part and Process Design	6	4	16
3	Wei and Egbelu (2000)	A Framework for Estimating Manufacturing Cost from Geometric Design Data	5	1	20
		Total Questions = 26			

The rating system should not be viewed as conveying that the articles lower in ranking are not worthwhile or have lesser value. Any approach selected in this "top ten" list has positive characteristics.

Table 8.8 Percentages of Positive Results by Question

		Total Yes	Total Maybe	Total No	Positive %(Y+M)
Q	Category 1: Inputs				
1	Approach does not require an interface to a conceptual design file	4	2	4	60
2	Approach does not require a nearly complete drawing	5	2	3	70
3	Approach does not require a nearly complete process plan	10	0	0	100
4	Approach does not require a specialist user	8	2	0	100
5	Approach does not require user to make assumptions on manufacturing tasks	9	0	1	90
6	Approach does not require user to categorize part features	9	0	1	90
	Category 2: Regeneration of Results				
7	The logic and underlying data used by the approach is presented in a manner that can be recreated by the reader	3		7	30
8	Underlying production rules, sequencing logic, and cost information is presented in a manner that would facilitate the creation of a working system	0		10	0
	Category 3: Processes and Costs				
9	All major processes required to complete a machined part are addressed	4	0	6	40
10	Manufacturing cost addressed	10	0	0	100
11	Tooling cost specifically addressed	3	1	6	40
12	Planning cost specifically addressed	0	0	10	0
13	Timing of expenditures is considered (time value of money)	2	0	8	20
14	Overhead is not applied discretely based on part characteristics	7	0	3	70
15	Learning factors were considered	0	1	9	10
	Category 4: Scheduling				
16	Approach includes scheduling considerations	2	0	8	20
	Category 5: Tooling				
17	Tooling and/or fixturing is considered	10	0	0	100
18	Discrete tooling requirements are considered	1	2	7	30
	Category 6: Planning				
19	Planning tasks are considered as part of the project plan	0	1	9	10
	Category 7: Manufacturability				
20	Approach includes manufacturability verification	8	1	1	90
21	Production rules used by manufacturing are part of design verification	7	1	2	80
22	Manufacturability examples are provided for key processes	1	0	9	10
	Category 8: Project Management and Information Reuse				
23	Approach recognizes the need to reuse information from similar products	4	0	6	40
24	Approach links data to the systems of downstream users/activities	1	1	8	20
25	The cost data could be rolled into other financial forecasting systems	0	3	7	30
26	Output would allow for capacity analysis	1	2	7	30

8.4 Discussion of Assessment Tool Results

The assessment tool clearly shows there is a wide-range of approaches in the literature dealing with conceptual design decision-making. Most approaches do not consider all of the activities in the IDEF0 diagrams (i.e., Chapter 2, pages 52-55) in their methodologies or systems, but instead narrow the focus to smaller segments of the generic product development process. The following paragraphs provide a category level discussion of results.

8.4.1 Category 1: Inputs

Most of the samples did well in this category overall. However, the weaknesses of some approaches were the requirements for a nearly complete drawing or a link to CAD. The systems investigated require a level of data detail likely not available during early conceptual design.

8.4.2 Category 2: Regeneration of Results

This category shows a potential weakness in the approaches currently found in the literature. It is understandable a journal article is not going to have the same breadth of detail as a dissertation. However, a journal article should convey enough information for the user to be able to envision application of the methodology conveyed to a new problem. There are many journal articles promising future work to fill in these types of detail, and the results of future work cannot be located after many years have passed.

8.4.3 Category 3: Processes and Costs

Most of the samples did well in providing some explanation as to how they derived total manufacturing costs. However, many but did poorly in recognizing that an IPT needs visibility to more than one process to develop finished designs. The approaches also did poorly with regard to considering the timing of expenditures, learning factors, and planning costs.

8.4.4 Category 4: Scheduling

Most of the samples did not consider scheduling issues at all, and only two presented some cursory scheduling related information. In most instances, cost values were presented without explanation of the role of timing of expenditures, i.e., scheduling. While some might argue that all an IPT needs are relative timeframes (and therefore, relative costs) this philosophy likely leads to suboptimal enterprise decisions in the long run. As discussed in Chapter 5, working-level IPTs are tasked to consider resources, capacity, line balancing, and associated costs in the context of a specified timeframe of occurrence in order to make real decisions. In addition, the estimates the IPTs generate during conceptual design should be relatable to estimates developed by the Business Management and Factory Management activities or cost deltas calculated have little real value. Also, if IPT users must make comparisons to outside suppliers, then this comparison cannot be made without making requirements and associated costs *real*.

8.4.5 Category 5: Tooling

Several of the samples considered tooling cost in some way, but did not provide insights as into the initial development of design tooling requirements. The tooling costs associated with building a design quite often dwarf the first-article cost to produce the design. In addition, the identification of tooling requirements has a far greater impact on project management than a dollar value. Hence, understanding how design decisions map to tooling decisions is a critical aspect of generating good cost and schedule estimates, as well as reducing total product cost and time-to-market.

8.4.6 Category 6: Planning

Most of the articles in this assessment did not consider the planning activity’s involvement in the creation of work instructions as a key deliverable for an IPT or as a component of manufacturing cost. Several of the approaches focused on estimating a cost value, as opposed to a project plan with specific deliverables that can be related to the estimate of cost.

A planner is typically a member of an IPT, and work instructions play an important role in routing, work order generation, tool ordering, etc. An IPT project plan for a design would likely include a work instructions deliverable, which is scheduled and monitored in the real world.

8.4.7 Category 7: Manufacturability

Most of the samples discussed the need to consider manufacturability, and stated that their approaches considered production rules. However, few provided examples of manufacturability rules being applied in a meaningful way. It is difficult to visualize how the logic found within modules shown on a diagram would be created and applied.

Several articles repeated high-level philosophies or “buzz phrases” that have been echoed multiple times in the literature. It is easy to make the assertion that *the best design has fewer parts*, but this broad statement is not always “true.” Many times the assembly sequence does not allow detail parts to be manufactured in one piece, all holes to be pre-drilled in fabrication, etc.

8.4.8 Category 8: Project Management and Information Reuse

This category is by far the weakest element of most of the ten approaches, as well as the literature reviewed during the course of this research. At the beginning of many articles, there is an explanation of the need to utilize concurrent engineering principles and integrated systems for project knowledge reuse. Then, many proceed to develop an output that does not directly interface with the information systems of downstream users or activities. Also, there is little to no recognition that the reason for generating a result is to contribute to the overall enterprise management of accomplishment.

Further, based on this author’s work experience, it is questionable if the results generated by some sample approaches would be any more effective than combining an estimator’s worksheet with a list of design guidance rules. Just because something is done in a new software package does not make it an improvement over current methods.

8.5 Conclusions

The results of the qualitative assessment tool mirror the types of knowledge gaps found in many approaches discussed in Chapter 3, Literature Review, as well as articles that are not used or referenced in this research. After reading hundreds of articles, there was always something missing with regard to how various approaches dealt with the product development process, concurrent engineering, IPT conceptual decision-making, the definition of design requirements, and/or the identification of manufacturing constraints and opportunities.

The results of applying the qualitative assessment tool indicate that reciprocal interdependencies management (RIM) concepts discussed and demonstrated in this research are useful in the IPT conceptual design decision-making process. Further, this research represents a positive contribution to the body of knowledge because it considers a broader spectrum of information than the average published work, as indicated by relative comparisons of the eight categories discussed, i.e., inputs/entries, regeneration of results, processes and costs, scheduling, tooling, planning, manufacturability, and project management and information reuse.

CHAPTER IX

SUMMARY AND DIRECTIONS FOR FUTURE RESEARCH

In Chapter 1, the objectives of this research are stated as:

1) Systematically apply Verganti's findings and concepts (i.e., reciprocal interdependences, feedforward planning, selective anticipation, etc.) to demonstrate how they can be used to improve IPT decision-making during the early stages of product design in the defense industry, specifically aircraft manufacturing.

2) Concurrently address the information needs/issues associated with product development process obstacles, concurrent engineering problems, and feedforward planning knowledge management issues by developing the following:

    a. Generic product development process diagrams
    b. Definition of integrated product team members and decisions
    c. Conceptual framework for a RIM-based DSS for use during conceptual design of an aircraft NC machined bulkhead

3) Examine the potential usefulness of using RIM concepts in the construction of enterprise systems by comparing the defined RIM-base DSS to other approaches found in the literature.

In this chapter, the results of the research are summarized based on the objectives and potential directions for future research are discussed.

9.1 Summary

The accomplishment of research objective #1 is achieved within various chapters of the dissertation. In Chapter 1, reciprocal interdependencies, feedfoward planning, feedforward effectiveness, etc. are used to justify the need for the research. In particular, feedforward planning effectiveness is discussed in the context of aircraft manufacturing in the defense industry. Verganti's study reveals that feedfoward planning effectiveness is measurable using criteria such as the amount of rework, engineering changes, unanticipated product costs, and missed time to market estimates. In other words, if an enterprise is not doing well in these areas, then their feedforward planning effectiveness is less than desirable. DOD acquisition data for various programs support the assertion that there is room for improvement in the context of feedforward planning effectiveness.

In Chapter 4, RIM concepts are used to re-think some of the commonly held views of the product development life cycle, particular in the areas of knowledge availability and cost commitment. Information housed on the "right side" (after design release activities) of the generic product development process (GPDP) diagrams has feedforward planning potential to create knowledge for use by earlier activities on the "left side" (before design release activities) of the GPDP diagrams. RIM concepts of commonality and selective anticipation can be used to organize information from past endeavors and make it recognizable during conceptual design, significantly raising the design and non-design knowledge from a starting point of zero percent.

In Chapter 5, the reciprocal interdependencies existing between IPT members are explored within the context of specific decisions made during the conceptual design phase. It is determined that much of the literature does not recognize the true task complexities involved in teaming decision-making, and based on Chapter 1 discussion of needs, there is a need to provide IPTs with systems and tools to assist them with decision-making.

In Chapter 6, RIM-diagramming is used to systematically develop the conceptual framework of a decision support system. A feedforward planning model (FFPM) is presented which utilizes design selective anticipation features and manufacturing selective anticipation features to provide the IPT members with a plethora of useful information and decision cues.

The accomplishment of research objective #2 is specifically addressed in the following chapters:

- Generic product development process diagrams (Chapter 2)
- Definition of working-level integrated product team (IPT) members, typical deliverables, and types of decisions (Chapter 5)
- Conceptual framework for a RIM-based DSS for use during conceptual design of an aircraft NC machined bulkhead (Chapter 6)
- Other contributions:
    - The literature review organizes, and categorizes a significant sampling of literature using the GPDP IDEF0 diagrams presented in Chapter 2 as a frame of reference. The effort results in the creation of a synergism of new product development knowledge, which is another contribution of this research. (Chapter 3)

    - RIM-diagrams are not attributed to Verganti, but instead are a contribution of this research in the context of RIM application strategies. RIM-diagramming was *discovered* by trying to apply Verganti's high-level concepts of RIM to the specific case of aircraft manufacturing. In general, RIM-diagrams have a far left column for the reciprocal interdependencies (knowledge links) of technical, resources, and sequencing, and then other columns to the right labeled *common* and *new*, and then horizontally denoted as *internal* and *external*. RIM-diagrams help to organize knowledge in a more meaningful way and they highlight the fact that knowledge on new design endeavors is never really at zero percent. (Chapter 6)

    - RIM as a collection of Verganti's concepts within the framework of an application strategy. (Chapter 7, Figures 7.1 and 7.2)

In Chapter 6, conceptual framework of the RIM-based DSS offers the potential to assist the IPT with many types of decisions. A decision making instance and associated feedback are illustrated in a series of flow diagram in Figures 7.6 – 7.16, beginning on page 329.

The accomplishment of research objective #3 is specifically addressed in Chapter 8. The usefulness of the RIM-based conceptual DSS developed by this research is compared to ten other approaches found in available literature using eight categories. The ten approaches are representative of the research discussed in the literature review in Chapter 3. None of the approaches appear to be as comprehensive or complete as the conceptual framework presented in this research for early design decision-making with very limited information. The defined RIM-based DSS for NC machining is more meaningful to IPT decision making during the early stages of design based on the criterion of the qualitative assessment tool.

9.2 Directions for Future Research

There is a great deal of potential future research related to the use of RIM and feedforward planning in the development of enterprise information systems for conceptual design decision-making. These opportunities are discussed in the sections that follow.

9.2.1 Development of a Computerized RIM-Based NC Machining Prototype

The added tasks of software development and testing are not objectives of this research in part because of the estimated time and resources involved; but they are a logical maturity for future research. A great deal of time was devoted in organizing technical background information, data tables, and potential outputs in the course of developing the final form of the RIM-based DSS conceptual framework presented in Chapter 6. In actuality, many pages of data were generated that ultimately were not needed at this stage of the research; but they nonetheless assisted this author's thinking through the IPT decision making process. The creation of an automated, prototype RIM-based DSS for NC machining is the most likely direction for future research. Once software is selected, the conceptual framework presented in this research coupled with data already developed provides a solid starting point.

9.2.2 Development of a True Working NC Machining Prototype System

In this research, the data developed thus far did not come from one specific company or identified source. However, a real world relevant working prototype could be created if an industrial partner or government agency received access to a sufficient complement of company specific aircraft manufacturing data for NC machining. Working with an industrial partner would also provide an opportunity to improve upon the approaches by involving more real world users.

9.2.3 Expanding the Defined DSS

There are many potential processing category candidates for expanding the DSS conceptual framework. Forging and composite processes are candidates for future research. There is process overlap between forged designs and NC machined designs. Hence, it is anticipated that building a forging module would be fairly straightforward. Composites manufacturing, tubing, electrical fabrication, casting, molding, and other processes are also viable candidates. There are many possible future research directions.

9.2.4 Development of a RIM-Based DSS for Aircraft Assembly

If aircraft assembly were defined within the DSS, then the information could be coupled to generate a project plan beginning with the design effort and ending with final assembly completion. This type of information could be used to form the baseline structure of a *virtual manufacturing* system for an aircraft manufacturing enterprise.

Developing a RIM-based DSS for aircraft assembly would be an enormous undertaking. While projecting the time to install one detail, such as a bulkhead that is normally on a single installation drawing is not difficult to estimate, the estimation related to an installation drawing with multiple details is somewhat complex.

During conceptual design, to generate an assembly load sequence, one must take an estimated detail design list and create a load sequence with many baseline assumptions and ground rules. The task is further made difficult by the requirement to take factors such as subassembly, crew loading, line balancing, and fixture forecasting into consideration. Likewise, the balancing of assembly tasks between different laborers, i.e., structural, electrical, and plumbing access/sequencing adds to the overall complexity. Creating a full-up assembly RIM-based DSS prototype would be similar to creating several NC machining prototypes because of the many sub-processes that comprise "aircraft assembly."

9.2.5 Application of the Methodology to Another Industry

The approach demonstrated in this research has application in other industries. Examples are shipbuilding or helicopter manufacturing. Even though the processes highlighted or the patterns of information used might be different in these industries, reciprocal interdependencies exist, and hence, selective anticipation and commonality can be used to define and improve upon the exchange of information between IPT members and enterprise activities.

Even though this author has no experience in shipbuilding, on the surface, it seems likely shipbuilding is similar to aircraft component assembly. Aircraft component assembly is performed in large fixtures, and prototypes are assembled completely in one fixture. When crewloading has to be considered in conjunction with assembly tolerances and structural buildup, it is far more complex than fabricating a single detail design. Since repeatable patterns exist in aircraft assembly, it is logical that similar patterns exist in shipbuilding and helicopter assembly. Further investigation in different industries would provide insights into design progression analysis and patterns of data use.

9.3 Final Thoughts

After reading and studying hundreds of articles related to conceptual design decision making, one comes away a variety of impressions, and often, more questions. A few preponderances are:

1) Articles and dissertations published in the late 1980s, 1990s, and 2000s look surprisingly similar to those published in the last few years. The biggest change appears to be the sophistication in computer systems utilized to demonstrate concepts.

2) While many understand the need for enterprise systems that support conceptual design decision making, most publications do no put forth an appreciable amount of new knowledge. The most probable reason is the effort associated with developing these systems is tremendous, as illustrated by the amount of work to develop the defined RIM-based DSS for NC machining presented in this research.

As a side comment, this author contacted several authors who published papers that discussed starting a project to develop a DSS for conceptual design decision making; but no published follow-up works exist. The authors who answered inquiries said the effort was far more complex than they had imagined, and for one reason or another, their effort was deferred.

> 3) There is considerable opportunity in this field of study, and very likely some of the best models and approaches are closely held within the proprietary documents of commercial enterprises that do well in concurrent engineering, product development, and IPT conceptual design decision making.

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APPENDIX A

CONCURRENT ENGINEERING INVESTIGATION

APPENDIX A – Concurrent Engineering Investigation

The purpose of this investigation is to address the following questions related to concurrent engineering:

1) Based on published reports, have companies today adequately embraced the philosophy of concurrent engineering?

2) If so, have the claimed benefits been realized?

3) If not, what has stood in the way?

The outline below provides an overview as to how the remainder of this investigation is organized.

- Definitions of concurrent engineering and related terminology
- Benefits of concurrent engineering, simultaneous engineering, and product lifecycle management
- Have companies embraced the philosophy of concurrent/simulataneous engineering?
  - Success stories
  - Surveys
- Have companies adquately embraced the philosophy of concurrent/simultaneous engineering? If so, have the claimed benefits been realized.
  - Aerospace/Defense industry
  - Automotive manufacturing industry
  - Motorcycle manufacturing industry
  - Telecommunications industry
  - Commercial aircraft manufacturing industry

  - Decision Council Survey – United Kingdom
  - Conclusions
- If companies have not realized the benefits of concurrent/simultaneous engineering, what has stood in their way?
  - Poor planning and management of communication linkages and complexities
  - Specialized hierarchies of knowledge
  - Cultural aversion to detailed and methodical thinking
  - Cultural bureaucracy and systemic complexity
  - Conclusions
- Summary

A.1 Definition of Concurrent Engineering and Related Terminologies

Some other terminologies in literature are used nearly interchangeably with concurrent engineering, specifically simultaneous engineering and product lifecycle management. Beginning in the 1980s, concurrent engineering was the more widely used term, and subsequently the use of the terms simultaneous engineering and product lifecycle management emerged. If one compares the definitions of each approach, then it quickly becomes apparent they are very similar. The following representative definitions of concurrent engineering, simultaneous engineering, and product lifecycle management were found in the literature.

Concurrent Engineering is *“a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support." This approach is intended to cause the developers, from the outset, to consider all elements of the product life-cycle from conception through disposal, including quality, cost, schedule, and user requirements."* (Winner et. al., 1988.)

Concurrent Engineering is "*a systematic approach to integrated product development that emphasizes the response to customer expectations. It embodies team* *values of cooperation, trust, and sharing in such a manner that decision making proceeds with large intervals of parallel working by all life-cycle perspectives early in the process, synchronized by comparatively brief exchanges to produce consensus."* (Cleetus (CERC), 1992.)

Simultaneous engineering *"advocates concurrent consideration of all related issues for design of a product: its manufacturing and support processes, and a host of other fundamental engineering concerns in the early stages of product design."* (Roy et al., 1999.)

Simultaneous engineering *"is generally recognized as a practice of incorporating various life-cycle values into the early stages of design."* (Ishii, 1990.)

Simultaneous engineering*" involves carrying out the functions involved in introducing new products in parallel rather than in series."* (Schill and McArthur, 1992.)

Simultaneous Engineering (SE),*"which means parallelizing formerly serial executed product development processes*, and Concurrent Engineering (CE), *which means to cut processes into smaller sub processes or activities and parallelize them, both to achieve less product development time.*" (Vajna, 2005)

Product lifecycle management (PLM) *"is the process of managing the entire lifecycle of a product from its conception, through design and manufacture, to service and disposal. It is one of the four cornerstones of a corporation's information technology structure. All companies need to manage communications and information with their customers (i.e., CRM-Customer Relationship Management) and their suppliers (i.e., SCM-Supply Chain Management) and the resources within the enterprise (i.e., ERP-*

Enterprise Resource Planning). In addition, manufacturing engineering companies must also develop, describe, manage and communicate information about their products." (CIMData, 2007.)

For the purposes of this investigation, it was assumed concurrent engineering and simultaneous engineering and are close enough in definition to be viewed as the same with regard to searches and discussion.

A.2 Benefits of Concurrent/Simultaneous Engineering, and Product Lifecycle Management

The potential benefits of CE, SE, and PLM are well-documented in the literature. Representative examples of potential benefits are provided in the quotes that follow. Again, the potential benefits read very much the same for all three approaches.

Concurrent engineering *"offers the potential benefits of reduced development time, the ability to uncover design flaws earlier in the development process, fewer engineering changes, improved quality, increased white collar productivity, and higher return on assets*." (Schultz, 1996)

"Simultaneous engineering increases competitiveness…. Competitiveness boils down to the successful development of management and the deployment of new techniques to get better products to the market faster." (Preface, Roy et al., 1999.)

Product Lifecycle Management *"offers the potential benefits of reduced time to market, improved product quality, reduced prototyping costs, savings through re-use of original data, a framework for product optimization, reduced waste, and savings through complete intergration of engineering workflows."* (Day, 2002.)

A.3 Have Companies Embraced the Philosophy of Simulataneous Engineering?

In order to determine whether companies have embraced simultaneous engineering, the literature searches for success stories and surveys related to concurrent engineering were performed. The results of these efforts are presented in the sections that follow.

A.3.1 Success Stories

There are many concurrent engineering successes documented in the literature. Some of the companies acknowledging success include AT&T, Xerox, Motorola, Harley Davison, and various Japanese endeavors. (Trygg, 1993; Harley Davidson, 2007.)

Small-scale concurrent engineering success stories within various organizations are the most prominent in the literature. Large-scale, enterprise-wide efforts are not as well documented beyond the press release level. (Wheeler et al., 1991; Bennett and Lamb, 1996.) Small-scale examples:

- Hewlett-Packard – a particular oscilloscope
- Cisco Systems – individual Internetworking products
- ITEK – specific optimal systems
- Raytheon – specific software engineering projects
- Ingalls Shipbuilding – SP-8 panel

A.3.2 Surveys

Most published surveys indicate that companies claim to be using concurrent/simultaneous engineering.

- Lawson and Karandikar (1994) report that a survey of U.S. businesses indicated that the use of concurrent engineering had become the *de facto methodology* for product development.

- Waterson et al. (1999) found that the majority of firms in the U.K. employing more than 150 people claim to utilize concurrent/simultaneous engineering practices.

- Portioli-Staudacher et al. (2003) report most industries located in the European Union member states of Italy and Belgum also use concurrent simulataneous engineering.

Based on a sampling of information sources, the answer to the question as to whether companies have embraced the concept of concurrent/simulataneus engineering appears to be "Yes."

A.4 Have Companies Adequately Embraced the Philosophies of Concurrent/Simultaneous Engineering? If So, Have the Claimed Benefits Been Realized?

If one considers the definitions of concurrent and simultaneous engineering and what they entail, then it sounds very much like "common sense." In fact, it would be difficult to understand why any company would not attempt to embrace the philosophy. If one looks at the potential benefits of concurrent/simulateous engineering, a company would seem foolish not to strive for these benefits. *What company does not desire improved time to market, better quality, lower cost, and increased competitiveness in the global marketplace?* Therefore, the real issue is likely what steps companies have actually taken related to embracing the philosophy of concurrent/ simulateous engineering, and how effective these efforts have actually been.

In order to answer the questions posed, a two-pronged approach was taken. First, survyes related to concurrent/simulataneous engineering performance was queried. Second, simultaneous engineering performane by industry sector was queried. Only one survey was discovered that discussed concurrent/simulataneous engineering efforts, and it was performed in the United Kingdom. No quantitative data related to sectors was found, so an inferential approach to the discussion based on concurrent/simultaneous engineering performance by industry sector was undertaken.

In the sections that follow, the findings for the following industries and the United Kingdom survey are discussed:

- Aerospace/Defense Industy
- Automotive Manufacturing Industry
- Motorycle Manufacturing Industry
- Information Technology Industry
- Commercial Aircraft Manufacturing Industry
- Decision Council Survey – United Kingdon

A.4.1 Aerospace/Defense Indusry

In 1989, General Dynamics, Fort Worth Division publically committed to the switch to concurrent engineering philosophies and integrated product development (IPD). The expected benefits to be derived were improvement of internal processes, improved quality, lower costs, and shorter delivery times. (Petrushka et al., 1990.) [This author actually worked with authors.] In 2006, the same facility (now owned by Lockheed Martin) just produced the F-35 Joint Strike Fighter with the some of the greatest recorded cost and schedule overruns in history. (Groot, 2006.)

Similiary, in 1988, the Institute for Defense Analysis touted similar expections for the application of concurrent engineering in all weapons systems acquisition. (Winner et al, 1988.) However, these expectations have not come to fruition. Over $1 Billion was expended on the X-33 Reusable Launch Vehicle, and the program was ultimately cancelled due to overruns. The International Space Station was originally bid at a total cost of $8 Billion and supposed to be operational by 1995, yet it is still under construction and the current estimated cost at completion has ballooned to $100 Billion. (Wynn et al., 2005.)

Hence, one can reasonably conclude based on performance, the defense industry has very likely not adequately embraced the philosophies of concurrent/simultaneous engineering.

A.4.2 Automotive Manufacturing Industry

In the late 1980s, Ford started its Alpha Simulataneous Enginering Program in response to Saturn’s touted successes. According to Ford, *“Alpha not only solved lots of engineering problems at Ford, it trained hundreds of Ford engineers in concurrent engineering methods and tools.”* However, after over ten years of Alpha, Ford still took over six years to develop a model with some of the highest development costs in the world. Similarly, General Motors (G.M) brought Saturn into the company in an effort to incorporate concurrent/simultaneous engineering. (Fleischer, 1996.) However, in last few years, both GM and Ford have continued to lose market share, competitive ability, and have record losses. (Nussbaum, 2006.)

The new Toyota Camry was launched in Australia at the end of 2006. According to Toyota, *"this car is the first of the international market Toyota vehicles to benefit from true simultaneous engineering."* The effort on the new Camry took place in Japan, the United States, Thailand, China, Taiwan, and Australia. Countless details about the car's design and manufacture were worked out in advance, even down to the most minor assembly issues. Toyota's primary goal was to avoid costly re-engineering, rework, and quality issues. The work on the new Camry was launched in 1996, and spent ten years in the development stage. While Toyota's time to market has not always been the fastest in the automotive industry, it has been one of the most effective in terms of quality results. (World Car Fans, 2006.) Toyota's vision is one of long-term quality.

At the outset of new Camry project, Toyota set goals to slash the development cost by 30%, put more features into the new Camry, and keep the sticker price near current levels. Dana L. Hargitt is an executive at Toyota who worked 20 years at GM prior to joining Toyota in 1996. When asked about concurrent/simultaneous engineering, Hargitt said that it is something performed at many companies, yet many snags exist in the way in which it is carried out.

Too often, concurrent/simultaneous engineering meetings turn into coffee klatches, and lack a systematic approach to problem solving. While there is cross-functional involvement, the resources of the organization are not committed to the endeavor.

Hargitt went further and said that it was *“a statement of the obvious”* if a company says it practices concurrent/simultaneous engineering and its sales figures are *“headed to the Grand Canyon,”* then it probably isn’t really practicing it. Simultaneous engineering has potential, but if not implemented properly, it does nothing to leverage resources, and only adds to decision-making complexity. (Vasilash, G., 2001.)

Hence, one could agree with Hargitt that automakers performing well likely have adequately embraced concurrent/simultaneous engineering and those performing poorly are likely inadequate in application.

A.4.3 Motorcycle Manufacturing Industry

Concurrent/simultaneous engineering is touted as one of the major reasons why Harley Davidson (HD) was able to reinvent itself during the 1980s. In 1983, the Reagan administration imposed tariffs on Japanese motorcycles to protect HD, and give it time to make a turnaround. By 1987, HD made the unprecedented request to have the tariffs removed. Harley-Davidson reported international sales in motorcycles rose 15% in 2005, and domestic sales grew 4.2%. (Harley Davidson, 2007.) In early 2006, Harley Davidson opened its first dealership in China in more than 50 years. (BBC News, 2006.)

Hence, one can conclude that Harley-Davison is one the right track with regard to its implementation of concurrent/simultaneous engineering philosophies. HD continues to create exiting products and maintains increasing market share.

A.4.4 Information Technology Industry

In 1995, Alcatel-Lucent (Alcatel-Lucent, 2007.) reported using concurrent/simultaneous engineering on projectes for AT&T, and in 2006, it reports using the philosophy to improve the IMS infructure. Likewise, Cisco Systems (Cisco Systems, 2007.) reports utlizing simultaneous engineering, and it is one of the best performing companies of its kind.

Based on performance, one could conclude that some companies within the telecommunications industry are adequately embracing the concurrent/simultaneous engineering philosophies.

A.4.5 Commerical Aircraft Manufacturing Industry

Concurrent engineering is touted as one of the major reasons for the success of the Boeing 777. In the 1970s, the Boeing 777 was the first aircraft produced entirely on a computer, with all drawings being done in CATIA. CATIA has many imbedded features, and facilitated virtual simulation of many interfaces without building expensive, physical prototypes. (Dassault Systemes, 2007.) However, by 2002, Boeing was in such bad shape that lobbyists proposed an Air Force lease plan labeled by many as a “congressional bailout.” (Schatz, 2003.) By 2003, Airbus had overtaken Boeing to become the world’s best selling aircraft maker. (BBC, 2005.)

Hence, based on performance, one could conclude that problems potentially exist with regard to how Boeing is implementing concurrent/simultaneous engineering philosophies.

A.4.6 Decision Council Survey: United Kingdon

Only one survey related to concurrent/simultaneous engineering was located, and it is approximately 15 years old. The survey is published in an article by Constable (1993). The Decision Council conducted a survey through the magazine *Engineering* in the UK. Over 700 replies were received. The following is a summary of interesting findings related to concurrent/simultaneous engineering projects:

- 50% reported products were taking longer to get to market
- The average cost overrun was 19% and the average schedule overrun was 27%
- On an average, 10-20% of design changes were initiated after design release

A.4.7 Conclusions

The results of the survey in the United Kingdom indicate companies can have problems implementing concurrent/simulataneous engineering. Likewise, the sector analysis shows some companies are doing well with regard to implementing concurrent engineering, while others are not.

In conclusion, whether companies have adequately embraced concurrent/simultaneous engineering principles varies from company to company. Since most companies do not publish specific information with regard to their shortcomings, unless of course they are reporting to have overcome them, it is difficult to know with certainty the reasons why companies perform poorly. However, if a company is adquately embracing concurrent/simultaneous engineering principles, it should be expected to do generally as well as other companies in the same industrial sector. Also, the benefits of improved cost, time to market, and quality should be apparent.

For some companies, such as Toyota, Cisco Systems, and Harley-Davidson, it is reasonable to conclude that real benefits have been realized, in that, these companies are recognized as world leaders in their particular business sectors. For companies that are having significant development cost and schedule issues, such as Ford, General Motors, and Lockheed Martin, it is reasonable to conclude that these companies are having problems realizing the benefits of concurrent engineernig for reasons that may not be readily apparent.

A.5 If Companies Have Not Realized the Benefits of Simultaneous Engineering, What Has Stood in Their Way?

If companies are doing poorly in realizing the benefits of concurrent engineering, then it is likely they are trying to answer this very question. If the answer was easy, then obviously, these companies would fix their problems. In reviewing the literature, some general problems regarding simultaneous engineering implementation were discovered. The issues listed below are discussed in the sections that follow:

- Poor management of communcation linkages and complexities
- Specialized hierarchies of knowledge
- Cultural aversion to detailed and methodical thinking
- Cultural bureaucracy and systemic complexity

A.5.1 Poor Planning and Management of Communication Linkages and Complexities

Due to there being many concurrent/simultaneous engineering success stories in the literature, a host of companies adopted CE/SE in an effort to shrink lead time. However, the complexities of communication linkages are not fully explored in the literature discussing CE/SE. (What sounds so simple…is not so simple.)

Hoedemaker et al. (1999) demonstrates that limits to the benefits of concurrency exist. As communication linkages within the organization become more complex, the less able concurrency is able to posititvely affect development time. In general, the more complex the organization and the project, the stricter the limits to concurrency, and the greater need to understand which decisions are affected by concurrency and which may not be. There are potentially adverse affects to placing too much emphasis on concurrency without fully exploring communication linkages.

Alcatel has achieved much success with concurrent engineering, but also reports that problems exist with concurrent engineering when the coding process is broken down into too many independent modules. The coding process for large programs for switching sytsems is attacked by dividing into modules. As the module size becomes smaller, the degree of parallel activity clearly increases. However, at the same time, the inefficiencies increase because of problems created by interfacing. As the communication burdens increase on individual programmers, the number of avoidable errors increases. (Hoedemaker et al., 1999.)

This author’s practical work experiences are consistent with these assertions. While teaming is inherently a good thing, if the communication linkages are not structured – and – the number of teams gets large - then it adds error to the decision making process. Typically individual members of teams are left nearly completely on their own to make decisions. Management provides little real direction on objectives or what is expected, and not much effort is placed on measuring individual performance. In addition, little formal training or decision support systems geared toward product development in the context of IPT decision making existed in the 1990s.

Historically, Lockheed's Skunk Works has been very successful in concurrent engineering, particularly when the number of people involved in the decision making process was smaller. The group accomplished phenomental things when decision making authority was closely-held. However, when the teaming arrangements got larger, and more companies became involved in the 1990s, the Skunk Works experienced new challenges. (This assertion is based on the authors work experience at the facility during the development of the the YF-22 prototypes.) In general, the more complexity involved in the decision making process, the more difficult it is to manage the outcomes.

Constable (1993) discusses that companies in the UK interpreted tcross-functional teaming and concurrent/simulataneous engineering reduces the need for management planning. The idea being that teaming should be done in an organic environment in a mutally supportive manner. This thinking appears to be opposite of what Toyota did on the new Acura.

Patrashkova and McComb (2004) developed a computational model to simulate cross-functional teaming effectives in a simultaneous engineering environment. They found that the having the entire team involved in every decision was ineffective. Instead, management should establish a framework where only requisite pieces of information required team involvement.

This author's work experience agrees with these assertions. It is difficult to determine the real cost versus benefit of unstructured IPT meetings. Quite often there are meetings of many inidividuals discussing issues that could easily have been solved using well-defined functional parameters. Likewise, involving individuals in meetings whose function is not affected is an added expense with little measurable benefit.

A.5.2 Specialized Hierachies of Knowledge

Winter (1999) discusses how specialized hierarchies of knowledge have played a role in the U.S. automakers ability to capitalize on the benefits of simultaneous engineering in an article titled, "Back to the Future? – Simultaneous Engineering." During the prolonged period of industrial growth in the 1960s, 1970s, and 1980s, many companies moved toward Adam Smith's theories of organization, and workers were organized by specialty. Government regulation also dramatically increased during this same time period, and this increase also added to automakers decision to create highly specialized hierarchies. Specific groups were formed inside corporations to coincide with particular regulatory legislation. (Winter, 1999). Similarly, the American education system followed suit, and the education system became more specialty oriented.

During the same period of time, Japan went through hard times, and had to become more efficient. Japanese automakers had to have staffs that were considered jacks-of-all trades. (Winter, 1999). Similarly, the education system *grew up* during the same timeframe, and emphasized broad-based skills, and was highly performance driven at the student level.

Ironically, the *jack-of-all-trades* philosophy was historically the philosophy in the United States prior to the 1960s. Hence, Winter implies that in order to solve some of their problems, companies are going to have to go “back to the past” and find, or train, employees and create systems which suppport more than one-dimensional, specialized problem-solving.

A.5.3 Cultural Aversion to Methodical Thinking

A great deal of U.S. culture has become adverse to methodical thinking. While the U.S. spends large sums of money on the education system, we are doing, on the average, poorly in mathematics and science. Hence, fewer individuals graduate from high school with the types of skills they need to function in an environment of incomplete information, such as new product development.

The typical IPT is reported to be composed of personnel with engineering degrees, personnel holding degress in some other discipline, or no degree at all. In general, these individuals resisted trying to systematically solve issues, and more often than not, operated out of something to do with their feelings or the desire for consensus. If everyone’s opinion is not appropriately validated, no matter how little fact they have to support it, it becomes a real problem.

As discussed earlier, Dana L. Hargitt is an executive at Toyota who worked 20 years at GM prior to joining Toyota in 1996. When asked about simultaneous engineering at GM, she said, …”*Too often, simultaneous engineering meetings turn into coffee klatches, and lack a systematic approach to problem solving.”*

Miller and Guimaraes (2005) discuss that one of the problems with cross-functional teaming is how it is managed. There are two types of control, behavioral and outcome. Behavioral control deals with how a task is accomplished, and outcome control deals with the results of the task. Effective cross-functional teaming requires both types of controls, but the emphasis at many companies has been very heavily weighted on the behavioral aspects of control, such as teamwork, communication, support, consensus, diversity, and validation.

This author’s teaching experiences support the assertions of Miller and Guimaraes. The majority of this author’s graduate business students do poorly in case analysis when it comes to quantitative assessment or methodical problem solving. In general, students tend to write about feelings, the need for communication, teamwork, consensus, validation the opinions of others, etc. These adult learners are evidently repeating back what they are being taught at work and in textbooks.

A.5.4 Cultural Bureaucracy and Systemic Complexity

For some companies bureaucracy and complexity are built into the very fabric of their culture. For example, the defense industry has many oversight agencies involved in the defense acquisition process, and its approach to doing business evolved in the era of cost plus contracting. Hence, unnecessary complexity and complex paperwork are part of the culture. It is going to be very difficult to make radical changes as long as the primary customer and *manager* of the acquisition process is the government.

Similarly, automakers have routinely had a lot of management involvement in routine decisions. Also, many employees in automotive manufacturers were conditioned by the *good times* of the past when they could make a high wage for doing one, specialized job function. Many human beings resist taking on added responsibility, learning new skills, or doing "their job" differently. (Winter, 1999.)

A.5.5 Conclusions

It is very difficult to pinpoint what specifically has stood in the way of companies realizing the benefits of concurrent/simultaneous engineering. If this answer were easy, then it is assumed that each company would figure it out. The four issues discussed are very complex in nature, and touch upon many aspects of enterprise decision-making, corporate culture, and the very fabric of American culture.

Unfortunately, sometimes when things are very inefficient, the only real "fix" is to break it down, and start over. Many U.S. companies in the news lately are restructuring to stave off bankruptcy, merging with other companies, or simply going out of business.

Unless a company has a monopoly or no real competition, it has little chance of surviving without using concurrent/simultaneous engineering concepts in today's global marketplace. If concurrent/simultaneous engineering principles are a competitive advantage (and most authors believe they are) as soon as one's competition becomes proficient, then the future is set. Either the company will compete, or it will start on the downward spiral toward ceasing to exist.

A.6 Summary

The purpose of this investigation is to address the following questions:

1) Based on published reports, have companies today adequately embraced the philosophy of concurrent/simultaneous engineering?
2) If so, have the claimed benefits been realized?
3) If not, what has stood in the way?

Based on published reports, most companies assert that they are using concurrent/simultaneous engineering. However, the success, or lack thereof, documented in the literature indicates not all companies have adequately embraced concurrent engineering philosophies.

For companies that have adequately embraced concurrent/simultaneous engineering their product development performance, market share, and quality indicate that they are indeed realizing the benefits. Toyota, Harley Davidson, and Cisco systems are good examples.

The main factors standing in the way of realizing the benefits of concurrent/simultaneous engineering seem to be rooted in how these companies implemented concurrent engineering, as well as historical and cultural attributes. Simply stated:

- If teaming is not organized and managed properly, then it will actually add complexity and error to the decision-making process.

- Specialized teams of personnel are not as efficient, or effective, as “jacks-of-all-trades” teams with broad-based knowledge and education.

- In general, Americans have moved away from structured and methodical thought processes to operating feelings. In many instances teaming, the desire for consensus, and the need for inclusiveness have created a *coffee klatch* approach to addressing problems.

- In some instances, the bureaucratic culture is still too prevalent, and it makes real changes in decision making difficult, if not impossible.

A.7 Implications of Dissertation Research on Improving Concurrent/ Simultaneous Engineering Implementation

In the sections that follow, the potential positive impacts to concurrent/ simultaneous engineering implementation efforts are discussed.

A.7.1 Specialized Hierarchies of Knowledge

The envisioned decision support system (DSS) and supporting databases potentially brings the information that has been separated into the functional systems used after design release back together into a format potentially useful for conceptual design decision making. The *whys* and, engineering requirements, resources allocations, and scheduling are in a format where the users can more easily understand the relationships between activities and decision making.

A.7.2 Reduction in Cross-Functional Non-Productive Teaming Meetings

The envisioned DSS organizes the enterprise lessons learned into a format that ultimately raises the foundation knowledge of the organization. The functional preferences are organized, and the feedback from the system potentially alleviates the need for redundant meetings. If the answer is available in the DSS, then there is no need for a meeting.

A.7.3 Improved Training

The envisioned DSS can be used as part of larger vision for IPT member training. The system assists with teaching new team members the methodologies and processes of aircraft manufacturing and how the results of their decisions affect others.

When the *jack-of-all-trades* philosophy was a part of the aircraft manufacturing mentality, design engineers desiring to be in management were required to complete a training program. The program involved working in various departments in the company to learn about their processes and tools. In addition, all employees had to go through training courses and learn about how the different functions operated.

Then, in the late 1980s, a new management theory was stressed that said a person did not need to be technically competent in a field to manage people working in that field. A manager needed to know about *management*, and his team would provide the broad based knowledge. At the same time, the need to learn technical skills outside of one’s own discipline was de-emphasized, and the employee training programs went away. The envisioned DSS strikes a balance between these two divergent approaches by organizing knowledge in a format where efficiently made available to individuals.

A.7.4 Movement Toward Methodical and Increased Outcome Controls

The availability and use of the DSS potentially emphasizes the need to make decisions based on facts and results. Hopefully, this will begin to move the emphasis away from feelings and the need to spend time validating opinions that are just incorrect and have no real basis of fact. In addition, the number errors in IPT decision making potentially decreases because the DSS provides checkpoints for a large number of decisions.

APPENDIX B

TECHNICAL INFORMATION REFERENCES

APPENDIX B – Technical Information References

The purpose of Appendix B is to offer additional references related to terms used within the dissertation, in particular Chapter 6. The sections of Appendix B are organized by topic. Some topics require merely a definition and references, while other topics are discussed more in-depth. The topics to be discussed are as follows:

- Aircraft product structure organization and naming
- Work breakdown structure (WBS)
- Design organization and numbering
- Common materials and related issues in aircraft manufacturing
- Processes used in aircraft manufacturing
- Material and process specifications
- Equipment specifications and process capability limits
- Standard parts manual
- Cost breakdown structure (CBS)
- Recurring and non-recurring cost
- Fracture critical and service life
- NC machining related processes discussed
- Tool codes
- Accounting and financial data
- Engineering and non-manufacturing deliverables
- Estimating rates and factors
- OSD escalation rates
- Performance and efficiency factors
- Learning curves
    - Learning curve methodology
    - Learning curve application
- Cost engineering
- Requirements engineering
- Process engineering

B.1 Aircraft Product Structure Organization and Naming

In order to define a potentially useful DSS for use in aircraft manufacturing, the terminologies and approaches used within the DSS to organize and describe a product the product structure information must be consistent with industry accepted practices. Aircraft manufacturing has an approach to the assignment of nomenclature that is well represented in the literature.

Examples of typical aircraft nomenclature, which includes the context of a general product structure, is available in various publications. The National Aeronautics and Space Administration (NASA) and other Department of Defense (DOD) organizations use nomenclature in various published reports and trade studies (Sensmeier and Jamshid, 2004; Dorsey, et. al., 1999). Also, aircraft nomenclature examples are found in university textbooks. (Brandt et al., 2004.)

Examples of nomenclature in the context of a product structure are as follows:

- Airframe
  - Forward, Center, Aft
    - Frame
    - Longeron
    - Shear web

It is interesting to note that a great deal of aircraft terminology was derived from shipbuilding terminology. The first aircraft designers looked to shipbuilding as a frame of reference. The aircraft industry uses similar terms like forward, aft, inboard, outboard, bulkhead, beam, frame, keel, rudder, and waterline. (Wisconsin Historical Society, 2004.) Other examples of common terminologies that provide additional insights to users with regard to care considerations are, flight critical, fracture critical, fuel area, pilot-safety critical, and redundant systems. These terminologies are found in various government publications and textbooks. (United States Army Corp of Engineers, 2000; Harris, D. et al, 2002.) Therefore, the type of product structure and nomenclature described in the previous paragraphs are used to define the conceptual framework presented in Chapter 6.

B.2 Work Breakdown Structure (WBS)

The Work Breakdown Structure (WBS) is a technique used in project management in which the project is broken down into manageable pieces. The WBS is often a listing of hierarchical tasks. (Meredith and Mantel, 2000.) The Department of Defense publishes the WBS guidelines for military contractors to use. (United States Department of Defense, 1998.) The Table that follows contains an example of a section of WBS structure for an aircraft system.

Table B.1 Work Breakdown Structure Example

Work Breakdown Structure			
Level 1	Level 2	Level 3	Level 4
Aircraft			
	Air Vehicle		
		Airframe	
			Structures
			Hydraulic Systems
			Electrical Systems
			Fuel Systems
			Environmental Control Systems
			Crew Station
		Propulsion	
		AV Applications Software	
		AV System Software	

The WBS designation is normally found in nearly every contract record maintained by military aircraft manufacturers because it must report performance in accordance to this structure. The WBS is recorded in systems that maintain engineering drawings, material purchases, shop orders, direct labor standards, budget forecasts, work instructions, master scheduling records, and performance reporting systems.

This research approaches the existence of the WBS as a baseline assumption in demonstrating the application of RIM strategies. The majority of the demonstration is done below the level of the WBS. (For example, a bulkhead is a part of the WBS for a component. A separate WBS does not exist for each detail design/part.)

B.3 Design Organization and Numbering

Aircraft manufacturers use a variety of numbering schemes to maintain control of the aircraft configuration and to support aircraft revision activity. The design-numbering scheme plays a critical role in how information is exchanged and reused. The careful selection of the "right" design numbering strategy is essential in analyzing historical data. (Kalagnanam et al., 2004.)

In many older systems, it was difficult to link "part numbers being assembly" and drawing numbers because the Manufacturing Bill of Material (MBOM) did not equal the Engineering Bill of Material (EBOM.) "Artificial" subassembly numbers were used, and it was often time consuming to properly link part numbers to the correct drawings.

The benefits of EBOM=MBOM approaches are widely referenced in the literature, as well in trade journals where vendors are offering software development services. Some examples of how EBOM=MBOM is being specifically used as a "ground rule" is in the development computer aided process planning systems and EBOM=MBOM mapping strategies. When EBOM=MBOM does not exist, it makes it very difficult to model responses in manufacturing because of the error. It is interesting to note that the majority of the current publications are in Chinese journals. (Johnson, 2007; Ou-Yang and Pei, 1999; Xuebao 2005.) Therefore, the assumption of EBOM=MBOM is used in this research.

B.4 Common Materials and Related Issues in Aircraft Manufacturing

The most common materials used in aircraft manufacturing are aluminum, titanium steel, stainless, steel, and composites. By far, aluminum alloys are the most popular materials in modern aircraft. (Brandt et al., 2004)

In many manufacturing enterprises, the material type is not maintained in the same system as the various production data, and is in an information silo. For example, one would have to enter a part number into the material department system to look up the material. Or, one would have to read the work instructions for a callout or reference. These types of difficulties are document in the literature as being obstacles to “economic” aircraft engineering as well as developing systems to assist in making quality and maintenance technical decisions. (Mirghani, 1996; Zinovev et al., 2007.) Therefore, the DSS defined seeks to provide a solution to the problems identified.

B.5 Processes Used in Aircraft Manufacturing

Airframe manufacturing primarily still utilizes mechanical subassembly assembly of detail parts. Further, these details are most commonly manufactured from these shaping processes; sheet metal fabrication, NC machined hog-outs, NC machined forgings, and composites fabrication. New technologies include laser forming, vacuum-die casting, and hot isostatic pressing, but these processes are not yet in widespread use to the point of taking over the traditional processing methods. (Martin and Evans, 2000; Mashl et al, 1997.) Therefore, NC machining is selected as the process to demonstrate the development of the conceptual framework of the DSS presented in Chapter 5. In addition, the concept of shaping is incorporated as a level on the conceptual process hierarchy presented.

The concept of organizing information in the context of “shaping” is not new, and the author does not intend to imply that this is a “new” way of organizing information. Instead, this information is offered to support why the decision was made for this research.

Additional aircraft manufacturing processes information is available as follows:

- Advanced materials and processes at Boeing (Smith, 2003.)
- 5-Axis and high speed machining case studies (Makino Corporation, 1998.)
- High tolerance machining center case studies for BAE Systems (NCMT, 2000.)
- Agile machining at Raytheon (Rose, 2002.)
- Virtual machining: Countersinking, counterboring, and spotfacing (Smith, 2005.)
- Metal processing and chemical milling (Aerospace Consumerist Consortium, 2005.)
- Solution heat treating (Seco/Warwick Corporation, 2005.)
- Alkaline degreasing and metal cleaning (Biospace Consulting Services, 2005.)
- Automated coldworking at Northrop Grumman (Bullen, 2001.)
- Coldworking analysis (Engineering Software and Research Analysis, 2001.)
- Coldingworking specifications (Kaman Aerospace, 2006.)
- Seal bonding (Chemical Containment Systems, 2006.)
- Cleaning and solvent use (Commonwealth of Massachusetts, 1994.)
- Cleaning and corrosion control (United States Air Force, 2004.)
- Metal degreasing (European Agency for Safety and Health, 2005.)
- Shot peening (Curtis-Wright Corporation, 2005.)
- Shot peening and fatigue life (Johnson, 2005; Sharp and Clark, 2005.)
- Non-destructive testing/penetrant etch (Esterline Corporation, 2004.)
- Penetrant inspection (Lockheed Martin Corporation, Quality Control Specification Index, 2006.)
- Bushing installation (Fatigue Technology, 2005.)
- Vibroengraving and marking (Hurel-Hipsano Meudon Company, 2005. United States Federal Aviation Administration, 2005.)

B.6 Material and Process Specifications

The appropriate selection and use of materials and processes (M & P) is critical to both the performance and the economic success of a product. When a particular material and/or process are used, the manufacturing enterprise is very meticulous about documenting the appropriate procedures to follow in something called "materials and processes specifications." The shop floor is required to adhere to appropriate material and process specifications to ensure that a quality part is produced. (Luttgeharm, 1990.) Further, these specifications even convey how a design produces by a process will be inspected. (Erickson. R, 2001; Lake, 1994.)

In some journal articles, authors imply that either engineering "doesn't know how to design" or that manufacturing "doesn't know how to manufacture." In essence, they do not recognize that if the manufacturing enterprise has used a process on a past design, that a great deal of information exists. The real problem is that the enterprise is not organized to use it again. The "enterprise" has the information, but individual IPT members have difficulty in making the connection to the information is in a silo. The IPT members often one or more of the following issues:

- Do not know the information exists.
- It is difficult for the average person to the information to an incomplete design because they have been not trained how to do this task.
- It is difficult to find the specific information needed for a specific design within the large amount of data that exists.

The aircraft manufacturing enterprise has spent expended a great deal of resources in developing the information for a different purpose, and only seasoned experts usually make the connection from past use to current use. Thus, the RIM concept of commonality can be used to develop a different approach in structuring information from the outset, provided that it is appropriately linked with a strategy for dealing with incomplete design information. This concept is presented in the development of the conceptual framework in Chapter 6.

B.7 Equipment Specifications and Process Capability Limits

A manufacturing enterprise purchases equipment and makes the decision to utilize certain processes because there is an ongoing need for the capability. When the equipment or machine is purchased, the manufacturer's specifications normally provide the key processing capability limits. Further, manufacturing engineering performs testing to verify capabilities before the new purchase is put into use.

An example is offered for an NC milling machine. Cincinnati-Lamb is a manufacturer of NC machines. Cincinnati-Lamb lists various equipment specifications on its company website for purchasers to reference as part of their decision-making. An example of information for a 5-axis machining system is listed below. (Cincinnati-Lamb, 2005)

Table B.2 Equipment Specification Example

5-Axis Machine Center	Machine 1
Table Size (inches)	137.8 x 66.9
X-Axis (inches)	157.5
Y-Axis (inches)	98.4
Z-Axis (inches)	29.5
A-Axis	± 40°
B-Axis	± 40°
Rapid Transverse (in/min)	945
Standard Spindle RPM	15000
Spindle Taper	HSK-63A
Tolerance - Hole Diameter	± 005
Tolerance - Hole Location	± 003
Tolerance - Surface Finish	± TBD

Even though fastening is not demonstrated in this research, another example of how capability information is “buried” exists in fastener specifications. Fastener manufacturers publish fastener specifications with their products. The aircraft industry has “common fasteners” that is uses, such as rivets, lockbolts, and eddie bolts. (References.) The following example from the process manual of an Eddie Bolt® fastener. (Alcoa Fastening Systems, 2004.)

Table B.3 Fastener Specification Example – Alcoa Fastening Systems

Nominal Diameter	Clearance Fit	Close Ream	Transition Fit	Interference Fit
5/32"	0.167	0.1645	0.164	0.1615
	0.164	0.1635	0.161	0.1595
	0.003	0.001	0.003	0.002

Based on work experience, it is asserted that the capability of “people” to drill holes without tooling assistance is not new information. It is “common knowledge” on the factory floor. “Manufacturing experts know” that a person cannot hold these tolerances without some type of tooling assistance. However, in countless conceptual design situations, estimators, manufacturing engineers, and others do not understand they CAN make inferences in cost and schedule decisions about tooling requirements based on nothing else but the identification of the type of fastener. The list of potential fasteners to be used is one of the first things that engineering typically does define.

As in the prior discussion involving M&P specifications, the same problem exists with regard to IPTs having access to capability information in a manner that makes it relevant to the new design decision they are considering. Again, many journal articles imply that the enterprise does not know its capabilities, and that the solution space is nearly infinite. RIM concepts are applied based on defining what you know in the context of multiple variables. When RIM concepts are used within the context of making decisions about an incomplete design, then the solution space narrows very quickly.

The DSS defined in Chapter 5 demonstrates how to organize technical information in a system that will start IPT members down the road to making faster and better decisions.

B.8 Standard Parts Manual

Each time a new aircraft is developed, engineers seek to use as many standard parts as possible. A standard part is manufactured in complete compliance with accepted industry and government specifications. The use of standard parts substantially decreases development and production costs. In most cases, a “Standard Parts Manual” is available that allows engineers to look up parts by type, dimensions, tolerances, etc. (United States Department of Transportation, Federal Aviation Administration, 1997.)

Based on work experience, the information in the “Standards Parts Manual” is normally in a stand-alone book or system that resides in the Engineering activity. In order to facilitate knowledge reuse, the standard parts information needs to be coupled with a systems and a strategy to use in the information during the conceptual design phase. Though this research does not demonstrate this part of conceptual design decision making, it is hope that in mentioning it that design experts will understand the RIM strategy in Chapter 5 and apply the strategy to assist IPT members.

B.9 Cost Breakdown Structure

A cost breakdown structure is a system for dividing and tracking costs at various levels, including project, hardware, functions and subfunctions, and cost categories. It is typically a hierarchical structure used to accumulate the expenditures of budgeted resources (i.e., dollars, personnel, facility, equipment, etc.) into elements such as direct labor, materials, and other direct costs. (Wideman, 2002.)

B.10 Non-Recurring and Recurring Cost

Non-recurring cost is a charge or expense that does not frequently occur in the normal course of doing business. It is often referred to as one-time cost or investment. Recurring costs occur repeatedly based on the number of units produced or amount of service performed. Recurring costs are sometimes referred to as variable costs. (Pallister and Daintith, 2006.)

The National Aeronautics and Space Administration (NASA) maintains an online, airframe cost model. The nonrecurring elements of this cost model are engineering, tooling, development support, and flight test. The recurring elements of the model are engineering, tooling, manufacturing, material, and quality assurance. As discussed within the dissertation, each organization and company is likely to have a unique set of definitions when utilizing the terms recurring and non-recurring. (NASA, 2005.)

B.11 Fracture Critical and Service Life

A very good discussion of the use of fracture critical and other service life terminologies in found within a documented titled, “Service Life and Design Analysis and Design Testing (DADT) Control Plan,” released for public use in 2006. (Bailey and Tashiro, 2006.) The website for this control plan is provided in the References of this dissertation. This service plan discusses the following categorizations:

- Safety of flight structure
    - Fracture critical I
    - Fracture critical II
- Non-safety of flight structure
    - Durability critical
    - Normal controls

B.12 NC Machining Processes Discussed

In order to fabricate a complete NC machined design, more than one type of work center is required, and more than one equipment option exists. There are many textbooks available that discuss machining fundamentals and processes. Most industrial engineering undergraduate students have some exposure to NC machining. In addition, the Internet has a plethora of information related to NC machining and related processes.

A very good source of information published by the United States Government can be found in a manual titled, “Pollution Prevention in Machining and Metal Fabrication – A Manual for Technical Assistance Providers.” (United States Environmental Protection Agency, 2001.) This manual is published by the Environmental Protection Agency (EPA,) and it provides an excellent overview of the machining industry by state, the types of processes used, process descriptions, and examples of process flow diagrams.

The most efficient method for determining which manufacturing processes that major aircraft manufacturers is to search their websites. In most cases, these companies have overview information about processes used, specifications, and descriptions available for potential suppliers and outside production organizations to peruse.

In developing the CBS work centers for this research, several major contractors websites were studied. Some websites contained information that might not be relevant to inexperienced users, while others contained details that even a novice would understand. The following is a list of useful documents found on corporate websites.

- Raytheon – " Control of Product Manufacturing Processes for Suppliers and Outside Production," March 2003.
- Raytheon – "Special Processes That Require RAC Supplier Approval," November, 2004.
- Boeing – "Special Process Source Approval," April, 2002.
- Boeing – "Supplier Specification Index," January, 2006.
- Lockheed Martin – "Engineering Requirements Flow Down Guide – LM Aero Supplier Guide," February, 2002.

B.13 Tool Codes

When tools are purchased, they are normally assigned a tool number in order to keep track of program costs, tool inventory, and maintenance schedules. In addition to a tool number, tools are also most often assigned a tool code, or tool template, in order to help the user quickly understand the type of tool. Tool codes are normally between two and six characters, and are shorthand versions of the tool type. For example, an assembly template tool might be coded ASTP or ASMT. A drill template tool might be coded DT or DRTMP. (Northrop Grumman, 2004.)

B.14 Accounting and Financial Data

Accounting and financial departments supply two key pieces of data/information that are necessary for consistent development of financial plans and forward pricing of future work. These pieces of information are:

1) M-Day schedule (4-digit number that is internally controlled)
2) Accounting month budgeted hours

In order for workload and resource plans to remain consistent, all departments inside an organization must utilize the same baseline for the number of workdays per month, and the number of hours that represents an equivalent man-month. Quite often, the accounting department will also add "payroll weeks" to the calendar. (Northrop Grumman, 1999.)

An illustration of an accounting month calendar is shown on the page that follows:

Table B.4 Accounting Month Calendar

January 2005 Accounting Month - 20 M-Days 160 hours

JAN

S	M	T	W	T	F	S
						1
2	3 1627	4 1628	5 1629	6 1630	7 1631	8
9	10 1632	11 1633	12 1634	13 1635	14 1636	15
16	17 1637	18 1638	19 1639	20 1640	21 1641	22
23	24 1642	25 1643	26 1644	27 1645	28 1646	29

February 2005 Accounting Month - 20 M-Days 160 hours

FEB

S	M	T	W	T	F	S
Jan 30	Jan 31 1647	1 1648	2 1649	3 1650	4 1651	5
6	7 1652	8 1653	9 1654	10 1655	11 1656	12
13	14 1657	15 1658	16 1659	17 1660	18 1661	19
20	21 1662	22 1663	23 1664	24 1665	25 1666	26

March 2005 Accounting Month - 20 M-Days 160 hours

MAR

S	M	T	W	T	F	S
Feb 27	Feb 28 1667	1 1668	2 1669	3 1670	4 1671	5
6	7 1672	8 1673	9 1674	10 1675	11 1676	12
13	14 1677	15 1678	16 1679	17 1680	18 1681	19
20	21 1682	22 1683	23 1684	24 1685	25 1686	26

Remaining March Calendar Days go into
April Accounting Month.

One of the main pieces of information that accounting and financial requires from manufacturing systems is the accurate gauging of percentage completion. Since large corporations utilize the accrual method of accounting, the percentage of completion method is utilized to recognize revenue for financial reporting. (Keiso and Weygandt, 1995.) In the defense industry, percentage completion is often tied to progress payments.

A common approach to determining percentage completion is to compare the planned hours for a task to the earned hours. Another approach is to compare the planned hours for shipset to the total earned hour to date. (Hawley, 2003.)

Before a job is put into work in manufacturing, an estimate of planned hours is normally developed. These hours can be standard hours or some other engineered hour basis. In addition, an estimate is established for the total number of hours an entire shipset (aircraft), so that an equivalent unit value can be calculated. (United States General Accountability Office, 1997.) The table that follows illustrates various percentage completion values.

Table B.5 Percentage Completion Illustration

	Planned Hours	Earned Hours	Percent Complete	Equivalent Units Complete
Job xxxx Planned Hours:	44.85	33.64	75.0%	NA
Shipset Planned Hours (Department):	5,455.68	33.64		0.0062
Shipset Planned Hours (TOTAL):	22,499.67	33.64		0.0015

	Planned Hours	To DATE Earned Hours	Percent Complete	Equivalent Units Complete
ALL JOBS IN WORK				
Shipset Planned Hours (Department):	5,455.68	3,245.89	59.5%	0.1443
Shipset Planned Hours (All Depts):	22,499.67	7345.67	32.6%	0.3265

Based on predetermined revenue guidelines, accounting will recognize revenue based on the calculated percent complete.

B.15 Engineering and Non-Manufacturing Deliverables

Engineering and non-manufacturing deliverables are those items created prior to manufacturing start. During the early stages of new product development, it is not uncommon for deliverables such as long-lead procurement, engineering drawings/designs, work instructions, tool designs, and supplier provided parts to be monitored. However, in most cases, the systems utilized are ad hoc, the procedures to populate the baselines are not standardized, and the data is difficult (nearly impossible) to reuse later.

According to a study released by the General Accounting Office in 2002 titled, “Best Practices: Capturing Design and Manufacturing Knowledge Early Improves Acquisition Outcomes,” one of the main drivers of acquisition cost is the management of the design release and other tasks (work instructions, tool designs, etc.) that occur prior to the actual start of manufacturing. For example, engineering management would include estimating the total number of engineering drawings, the projected release dates for drawings, and the percentage completion at key schedule points, such as the critical design review (CDR).

The GAO determined that the predominant cost and schedule growth driver was traceable to management of data that should have occurred prior to manufacturing start. When the manufacturing tasks are started prior to engineering design stability, the results are unfavorable. (United States Government Accountability Office, 2002.) A summary of the findings of the GAO are provided in the table that follows:

Table B6 The Affects of Achieving Design Stability After Manufacturing Start

Program	Average Drawing Completion at CDR	Product Development Processes* in Control	Average Cost Increase	Average Schedule Increase
AIM-9X	94%	Unknown	4%	1 month
F/A-18E/F **	56%	76%	0%	3 months
F-22	26%	44%	23%	18 months
PAC-3	21%	35%	159%	39 months
ATIRCM/CMWS	21%	0%	182%	34 months

* Processes include tools that link knowledge to decisions about the products' design and manufacturing processes prior to commitments of company resources are made.

** Earlier versions F/A-18 had demonstrated some component designs and materials. Hence, some design stability knowledge may not be reflected in the drawing count.

AIM-9X - Air-to-air missile carried by Navy and Air Force
F/A-18E/F - Fighter; F-22 - Tactical Fighter; PAC-3 Patriot Advanced Capability Missile Program
ATIRCM/CMWS - Advanced Threat Infrared Countermeasure/Common Missile Warning System

(GAO-02-701, "Best Practices: Capturing Design and Manufacturing Knowledge Early Improves Acquisition Outcomes.")

If an engineer is required to release a detail design to manufacturing before the overall design is stable, this situation creates risk, and increases the probability of cost and schedule growth. Even if an engineer designs a drawing that manufacturing can produce, it doesn’t matter if the drawing has to be revised later due to design changes that were totally out of his/her control. This type of “rework cost” situation is fundamentally different from engineering creating designs that cannot be manufactured, or designs that will require more expensive processing.

It should be intuitively understood that engineering and other functional departments, like planning and tool design, would benefit from using systems that are similar in nature to those already in use by the manufacturing department. Some companies already utilize similar approaches. A schedule of tasks/deliverables is created for the entire program, along with estimated labor requirements. Then, the personnel charge labor to the specific task. The end result is a management plan for monitoring the engineering release and supporting functions that must take place prior to manufacturing start.

B.16 Estimating Rates and Factors

In many estimating organizations, there is an entire group devoted to developing rates and factors to be applied in estimates. This group is responsible for developing various rates and factors in the formats required for enterprise systems, as well as customer required reporting.

The dollar rates are normally established based on current and projected dollar amounts paid for salaries and fringe benefits. These numbers are normally categorized in various groups, such as direct manufacturing, direct material, engineering, and indirect support. For example, if the average hourly worker is paid $15 per hour in salary in a given year, and the value of fringe benefits is estimated to be 55% of base salary, and then the system would utilize a value of $23.25 as the base year dollar rate for this class of labor.

A manufacturing enterprise normally maintains a variety of estimating factors. Some of the most common examples of factors can be found in a study done by RAND Corporation, published in 2001. Six major airframe manufacturers contributed to this study – Boeing, Hexcel, Lockheed Martin, Northrop Grumman, and Sikorsky. In this study, factors are demonstrated by labor type and material. In the study, the ratio reported are the airframe hours per pound of labor category by material to manhours per pound for aluminum for that labor category. The labor categories reported were as follows:

- Nonrecurring engineering labor
- Nonrecurring tooling labor
- Recurring engineering labor
- Recurring tooling labor
- Recurring manufacturing labor
- Recurring quality assurance labor

Examples of the cost ratios reported in the RAND study are illustrated in the tables that follow.

Table B.7 Cost Factors Example – Material Unity Factor

Cost Ratios from Rand Study
Military Airframe Costs: The Effects of Advanced Materials and Manufacturing Processes

NR - Non-Recurring R- Recurring

Material	NR Engr.	NR Tooling	R Engr.	R Tooling	R Mfg.	R QA
Aluminum	1.0	1.0	1.0	1.0	1.0	1.0
Aluminum-Lithium	1.1	1.2	1.1	1.1	1.1	1.1
Titanium	1.1	1.4	1.4	1.9	1.6	1.6
Steel	1.1	1.1	1.1	1.4	1.2	1.4
Carbon-epoxy	1.4	1.6	1.9	2.2	1.8	2.4
Carbon-BMI	1.5	1.7	2.1	2.3	2.1	2.5
Carbon thermoplastic	1.7	2.0	2.9	2.4	1.8	1.8

(Younossi, Kennedy, & Graser, 2001 – Rand Corporation)

Another approach to apply estimating factors utilizes the estimated task hours of direct labor as the unity. For example, estimating will use actual hours, standard hours, or some other approach to estimate the amount of touched labor hours required to manufacture a part or component. Then, estimating will apply factors to estimate the number of labor hours required by other related categories. Lastly, estimating applies labor rates to forecast the costs of the other labor categories, such as engineering or quality assurance. (Younossi et al., 2001)

Table B.8 Cost Factors Example – Direct Labor Unity Factor

R-Recurring	NR-Non-Recurring					
	R Mfg.	NR Engr.	NR Tooling	R Engr.	R Tooling	R QA
	1.0	2.3	2.3	0.1	0.1	0.1
Hours	100.0	230.0	230.0	10.0	10.0	10.0
Rate ($/hr)	23.25	62.78	58.13	56.50	51.15	25.58
Estimate ($)	2,325.00	14,438.25	13,368.75	564.98	511.50	255.75

B.17 OSD Escalation Rates

In military aircraft manufacturing, it is most often necessary to forecast program costs for ten to fifteen years into the future. Hence, there is a basic procedure followed to estimate all program costs in order to make sure reporting is done in equivalent units and in a uniform fashion. Normally, a group of estimators works constantly to maintain the most up to date escalation rates to make appropriate conversions.

First, a base year is normally stipulated. For example, the contract may stipulate base year 2000 dollars. Next, the estimating rates and factors group will develop appropriate factors to use in the out years of the forecast in the stipulated base year dollar. These factors reflect projected increases or decreases in costs that are contractually agreed upon by the customer. Lastly, the final escalation rates are obtained from the Office of the Secretary of Defense and applied to create Then-Year dollar rates. (United States Office of the Secretary of Defense, Inflation Guidance, 2005.)

Table B.9 OSD Escalation Rates Example

APN = Aircraft Procurement, Navy (1506)

Base Year = 2005

Fiscal Year	Inflation Rate %	Raw Index	Weighted Index	Budget Year Index	Budget Year Inflation Rate %
2005	2.00%	1.0000	1.0267	1.0000	2.04%
2006	2.00%	1.0200	1.0480	1.0208	2.08%
2007	2.10%	1.0414	1.0700	1.0422	2.10%
2008	2.10%	1.0633	1.0925	1.0641	2.10%
2009	2.10%	1.0856	1.1154	1.0864	2.10%
2010	2.10%	1.1084	1.1388	1.1093	2.10%
2011	2.10%	1.1317	1.1628	1.1325	2.10%
2012	2.10%	1.1555	1.1872	1.1563	2.10%
2013	2.10%	1.1797	1.2121	1.1806	2.10%
2014	2.10%	1.2045	1.2376	1.2054	2.10%
2015	2.10%	1.2298	1.2635	1.2307	2.10%

B.18 Performance and Efficiency Factors

Standards are offer a consistent baseline of measurement for a manufacturing operation. Tasks are rarely completed in the hours allotted as the standard time. Since estimators strive to project realistic estimates, they utilize performance, or efficiency, factors to estimate actual labor hours. In some literature, this factor is also referred to as a realization factor. (United States Office of the Undersecretary of Defense for Acquisition Technology and Logistics, 2007; United States Office of the Undersecretary of Defense for Acquisition Technology and Logistics, Realization, 2005.)

The equation below illustrates the meaning of the factor:

$$P_E = \frac{A_T}{S_T}$$

Where:

P_E = Performance (Efficiency) Factor
A_T = Actual time to perform the task
S_T = Standard time to perform the task

Most manufacturing organizations maintain monthly and yearly reports on performance. For example, if an assembly department had an average performance of 75%, then its estimating performance factor, P_E, would be 1/0.75 = 1.34. Hence, if a job is determined to have a standard hour content of 15 hours, then the estimated actual hours would be determined as follows:

$$P_E = \frac{A_T}{S_T}$$

$$P_E \times S_T = A_T$$

(1/0.75) x 15 = 20 actual hours

B.19 Learning Curves

Learning curves are used in the defense industry to predict the amount of actual hours reduction that can be expected over a given amount of production. In basic terms, learning curve theory puts forth that the percentage reduction in actual hours will be constant over successively doubled unit quantities produced. The constant percentage is the rate of learning. The slope of the learning curve is 100% - rate of the learning percentage. For example, if a process is said to have a learning curve slope of 90%, that that means that the rate of learning is 10%. The hours between doubled quantities will be reduced by 10%. (United States Department of the Air Force, 2002.) Quite often, learning curves are applied using standard values as the basis. (Defense Contract Audit Agency, 2007.)

B.19.1 Learning Curve Methodologies

There are various methodologies under the heading of "learning curve." Two of the more common approaches are:

1) Unit Learning
2) Cumulative Average Learning

For simplicity, only one method is going to be illustrated. The following is the equation for Unit Learning:

$$Y_X = T_1 * X^b$$

Where:

Yx = the labor hours required to produce the Xth unit
T1 = the theoretical or actual labor hours of the first production unit
X = the sequential number of the unit for which the labor hours are being computer
b = the constant for the rate decrease from unit to unit

The logarithm transformation of the Unit Learning equation is as follows:

$$\ln(Y_{X)} = T_1 + b * \ln(X)$$

Where:

ln = The natural logarithm

The value of b is expressed in equation form as follows:

$$b = \ln S / \ln 2$$

Where:

S = the (cost or unit hours)/quantity slope expressed as a decimal value.

For example, if the first unit took 100 actual hours and the second unit took 88 actual hours, then the unit curve would have an 88% slope, and the value of S would be 0.88.

The value of b would then be equal to the following:

$b = \ln(0.88) / \ln(2)$

$b = -0.12783 / \ln(0.69315)$

$b = -0.18442$

The equation to determine the slope from b is as follows:

$\ln \text{Slope} = b * \ln 2$

$e^{b*\ln 2} = \text{Slope}$

B.19.2 Learning Curve Application

One of the more common applications of learning curve theory is the use of standard hours to project theoretical T_1 values. The Unit Learning equation is a follows from above:

$Y_X = T_1 * X^b$

In order to project theoretical T_1 values, the format of the equation is changed as follows:

$Y_X / X^b = T_1$

When this approach is utilized, the estimator must determine three important pieces of historical information:

1) The historical learning curve slope for the type of task being estimated.
2) The historical unit break point for standard value attainability. For example, if it historically took 100 units of production before the standard value was attainable,

then the value of X=100. (Some refer to this as the expected point to "bottom out" on the learning curve.)

3) The current average performance factor for the type of task.

Typical learning curve slopes for aerospace are as follows: Fabrication 90%, Assembly 75%, and Material 98%. (In the case of material, the above unit learning equation is converted to dollars as a basis.) (Wilcox, 2002.)

The calculations that follow illustrate typical theoretical T1 calculation procedures:

$Y_X / X^b = T_1$

Assembly Slope, S = 75%

$b = \ln(S)/\ln(2)$

$b = -0.41504$

Assume projected standard hours = 100.00

Assume performance factor = 1.34

Estimated production actual hours = 134.00

Table B.10 Theoretical T1 Projection Examples

Learning Curve "Bottom" Unit Number	Y_X (hours)	X^b	Theoretical T_1 (hours)	T_1/Y_x
100	134.00	0.14788	906.12	6.76
200	134.00	0.11091	1,208.16	9.02
300	134.00	0.09373	1,429.58	10.67
500	134.00	0.07583	1,767.20	13.19
700	134.00	0.06594	2,032.05	15.16
1000	134.00	0.05687	2,356.27	17.58

B.20 Cost Engineering

According to the Association for the Advancement of Cost Engineering (AACE, 2007) cost engineering is defined as *the area of engineering practice where engineering judgment and experience are used in the application of scientific principles and techniques to problems of cost estimating, cost control, business planning and management science, profitability analysis, project management, and planning and scheduling.*

B.21 Requirements Engineering

Requirements engineering (RE) is a term that is often used in the context of software development. RE is *understanding what you intend to build before you're done building it.* RE is broken down further into two subgroups, requirements development and requirements management. (Weigers, 2003.)

In recent years, a lot of effort has gone into creating computer systems to management requirements. These included material requirements planning (MRP) and capacity requirements planning (CRP). However, the “requirements development” activity has not been given as much emphasis in aircraft manufacturing. Requirements development is accomplished by IPTs or not done until after engineering release.

B.22 Process Engineering

Process engineering is *the application of knowledge, tools, and techniques to define, visualize, measure, control, and improve processes in a way that meets business objectives, i.e., customer requirements and profitability goals.* (Melan, 2002.)