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ORIGINAL ARTICLE

Multi-criteria approach using simulation-based balanced scorecard for supporting decisions in health-care facilities: an emergency department case study

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Abstract
Health research is a priority in every economy, and this research – set in the context of building a more sustainable and efficient health-care system – examines how operations management practices can be translated to clinical applications. Health-care systems in general (and emergency departments (EDs) in particular) around the world are facing enormous challenges in meeting the increasingly conflicting objectives of providing wide accessibility and delivering high-quality services efficiently and promptly. The framework proposed in this study integrates simulation modelling, the Balanced Scorecard, and multi-criteria decision analysis with the aim of providing a decision support system for health-care managers. Using the Analytic Hierarchy Process, simulation results are aggregated to achieve defined strategic as well as tactical and operational objectives. Communicating the significance of investigated strategies can encourage managers to implement the framework's recommendations in the ED within the partner hospital.
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Introduction

Health-care managers are currently under constant pressure to control rapidly escalating expenses, while still responding to growing demands for both high-class patient service levels and medical treatment. Resolving such challenges requires a consistent understanding of health-care systems, which can be an overwhelming task, given the large number and diversity of the organisations involved and their high levels of uncertainty and interdependence. Moreover, health-care managers also face the challenge of intrinsic uncertainty of the demands and outcomes involved in health-care systems; high levels of human involvement at both patient and staff level; limited budget and resources; and a large number of variables (e.g., staff scheduling, bed availability, etc.). As well as seeking high service quality levels, patients are, understandably, less and less prepared to wait in queues for essential health services, and thus the health-care service concept has shifted from optimising resource utilisation to finding the best balance between service for patients and efficiency for providers (Brailsford & Vissers, 2011). Dealing with the inevitable complexities in health-care processes and services and addressing the challenges involved in making informed decisions are the focus of this research. The objective of this paper is to develop a simulation-based decision support framework to improve planning and efficiency of health-care processes. A real-world case study of an emergency department (ED) in one of Dublin-Ireland largest university hospitals is investigated to help the hospital executive managers enhance patients' experience using the proposed framework.

Project background

Overcrowding in EDs has become a significant international crisis that negatively affects patient safety, quality of care, and patient satisfaction (Graff, 1999). Overcrowding in Irish EDs was declared a 'National Emergency' in Ireland in 2006. Several national reports have highlighted a growing demand for emergency care (1.2 million patients attending EDs annually) and a simultaneous decrease in the number of operating EDs. The results are increased crowding, high percentages of patients leaving EDs before completing their treatment episodes, and higher morbidity and mortality rates. In addition, prolonged waiting times have been reported with more than 500 patients on trolleys for hospital admission every day; 18% of patients are waiting more than 24 h and 40% between 10 and 24 h (Health Service Executive, 2010). Although Ireland is not alone in experiencing these figures (Schafermeyer & Asplin, 2003, Bond *et al*, 2007, Forero *et al*, 2010), it is important not to underestimate the sometimes catastrophic consequences this situation has for patients, staff, and the health-care sector.

This project was a joint effort involving hospital staff (managers, consultants, doctors, nurses, and administrators) and our institute research team. The university hospital is an acute care public hospital in North Dublin. This 570-bed hospital provides a variety of health-care services, with a 24-h 'on-call' ED that receives over 55,000 patients annually. According to the task force report in 2007, the overall physical space of the ED and infrastructure were inadequate. The hospital – which was operating at approximately 99% occupancy – had difficulty in accommodating surges in ED admission numbers. Therefore, patients who required critical care (ICU/HDC) beds suffered from significant delays and the ED could not meet the national target of 6-h average length of stay (LOS) for patients. The ED figures show clear evidence of this overcrowding, with an average of 17% of its patients choosing to leave before being seen by the ED clinician. The report also indicated that the average time from ED registration to discharge was 9.16 h, that is, 3.16 h over the 0–6 h metric set by the HSE, and the average time from registration to acute admission was 21.3 h with a standard deviation of 17.2 h (i.e., 3.5 times higher than the same national metric). Obviously, patients who are admitted will usually experience longer LOS times than those who are discharged due to delays between admission referral by an ED doctor, the allocation of a bed, and time taken to transfer the patient to the bed.

To cope with these challenges, a joint collaborative work was established with the hospital management team to develop a decision support framework. This collaboration aims to identify performance bottlenecks and explore improvement strategies to meet the HSE targets.

Proposed methodology

Literature review

Over the past two decades, several performance measurement systems have been introduced with the objective of achieving the full potential of performance measurement approaches (Fitzgerald *et al*, 1991, Kaplan & Norton, 1992, Lynch & Cross, 1995, Neely *et al*, 2002). Assessing performance is essential because it provides the capability to identify performance bottlenecks and take corrective action before these problems escalate (Kueng, 2000).

The Balanced Scorecard (BSC) is one of the main performance measurement frameworks that use strategy-linked leading performance measures and actions for planning and implementing an organisation's strategy (Kaplan & Norton, 1996). The BSC was discussed as an appropriate tool for health-care organisations as early as 1994, when Griffith (1994) placed the BSC in the broader notion of championship management. Several papers have described financial success stories using the BSC in health-care organisations, whether by solving financial crises (Jones & Filip, 2000, Meliones, 2000, Mathias, 2001) or by reducing costs (Berger, 2004, Colman, 2006). The BSC has also become a regular step in quality improvement within several health-care organisations (Moullin, 2004). It has become a tool for developing quality plans and for evaluating quality improvement processes (Colaneri, 1999, Peters & Ryan, 1999).

While the BSC has been applied successfully as a strategic management tool, there are many challenges in the design and implementation. The choice of performance perspectives and measures to be included in the BSC is one of the main challenges in designing BSCs in health-care settings. Furthermore, the number of performance measures is challenged by the amount of resources tied up in the measurement process, in terms of data collection and analysis and the representation and interpretation of the measures (Gao *et al*, 2006). Finally, the interactions between the performance indicators within the BSC are, in most papers, assumed and treated as unproblematic issues (Aidemark & Funck, 2009), ignoring the fact that several indicators can oppose each other (Patel *et al*, 2008). Because of the large number of variables and high levels of uncertainty, the BSC has to integrate with other analytical tools.

Several studies have combined multi-criteria decision analysis (MCDA) techniques with the BSC in order to overcome these challenges. The Analytic Hierarchy Process (AHP) (Saaty, 1990) is applied by many authors for the selection of performance measures to be used in the

BSC (Clinton *et al*, 2002, Searcy *et al*, 2004, Wu *et al,* 2009). Other multi-criteria analysis methods have also been applied in the design and evaluation of BSCs. For example, the Simple Multi-Attribute Rating Technique (SMART) can be used to select appropriate measures for the development of a BSC system in a financial institution (Valiris *et al,* 2005).

Despite the recognised importance of explicitly dealing with priorities and trade-off between different performance indicators (Banks & Wheelwright, 1979; Eccles & Pyburn, 1992; Da Silveira & Slack, 2001), limited literature has addressed the nature of the trade-offs between these measures and their inter-dependencies (Mapes *et al*, 1997, Neely *et al*, 2000). Understanding the causes of unsatisfactory performance levels and determining proper corrective actions requires, in most cases, understanding and detailed analysis of the underlined process and the consideration of trade-offs. However, the lack of analytical tools prevents decision makers from effectively processing all the information necessary in order to develop and implement better-informed decisions and plans. Consequently, modelling and simulation are required (Sterman, 1989; Senge, 1991).

Efforts to develop simulation models have advanced since the late 1980s when simulation was used to investigate the impact of key resources on waiting times and patient throughputs (Saunders *et al*, 1989), and it has since been used to study the effect of a wide range of health interventions on health-care processes' performance (Dittus *et al*, 1996; Kim *et al*, 1999; Ingolfsson *et al*, 2003; Litvak *et al*, 2008). Simulation models can effectively be used as a predictive tool to predict the maximum demand level that ED staff can handle, and consequently determine the required staffing level to meet that increase in demand and at the same time to keep the average waiting time of patients under a certain threshold (Baesler *et al*, 2003). A balance in the utilisation of resources would be attained by analysing the arrival pattern of patients, which can significantly improve staffing planning and resource allocation (Sinreich & Marmor, 2005. The bed occupancy level has been found to be strongly correlated with average LOS of patients within the ED (Forster *et al*, 2003). By using simulation models, Elbeyli and Krishnan (2000) found that adding beds to other specialised units within the hospital decreased the average time of patients waiting to be admitted to the ED.

Most of the prior simulation studies have used a single-perspective performance measure. Given the current complexity of the health-care systems, multiple perspectives of performance are instrumental in operational and strategic decisions. The BSC, MCDA, and simulation modelling are approaches that have independently proven their potential to inform and support the decision-making process. There is also a clear potential for these approaches to be integrated and applied in a collaborative manner that can bring new insights to inform and support the different stages of the decision-making process.

Proposed framework

The main objective of this framework is to address the limitations in the literature and to provide health-care managers and planners with an integrated decision support tool that can be used in an effective and practical manner. This section discusses the aspects and requirements for developing such a framework. Figure 1 gives an overview of the framework, and the following sub-sections provide detailed descriptions of each component, and highlight the coordination between them and their points of integration.

Business process modelling Defining the problem to be solved is one of the key elements in developing the framework. Health-care systems contain high levels of social interaction that are characterised by complexity, particularly at decision points, with the result that health-care service delivery and patient flow management problems are usually hard to define. Gaining a better understanding of the health-care process is essential for making correct and justifiable decisions and providing effective solutions, and therefore modelling the underlined business process requires that problems be understood from the point of view of the individuals directly involved in service delivery.

In order to provide a holistic view about various aspects of the system, the data collection phase combined interviews, focus groups, and quality circles with experts and the underlined business processes were then mapped onto a conceptual process model using one of the well-developed modelling languages where sub-processes and activities are identified. The control flow definition is created by identifying the entities that flow through the system (e.g., patients, staff) and describing the connections that link different parts of the process, and resources are identified and assigned to activities where necessary. The process model must be verified to ensure that it is logically valid and does not contain errors.

Simulation modelling The process model was combined with the analysed empirical data into a dynamic simulation model, so that both the data collection phase and the business process modelling take place within the context of developing the simulation model. The procedure is often referred to as model translation because it involves transforming an abstract conceptual model into a more detailed and complex executable simulation model. To ensure that the credibility of the simulation model can be guaranteed, it must be both verified and validated. Verification ensures that the transformation of the conceptual model has been applied correctly so that the model's logic reflects the underlying business process, while validation involves comparing the outcome data of the simulation model with the data obtained during the data collection phase (Balci, 1997). Once the simulation model is verified and validated, the decision makers can use the replicated model to investigate a

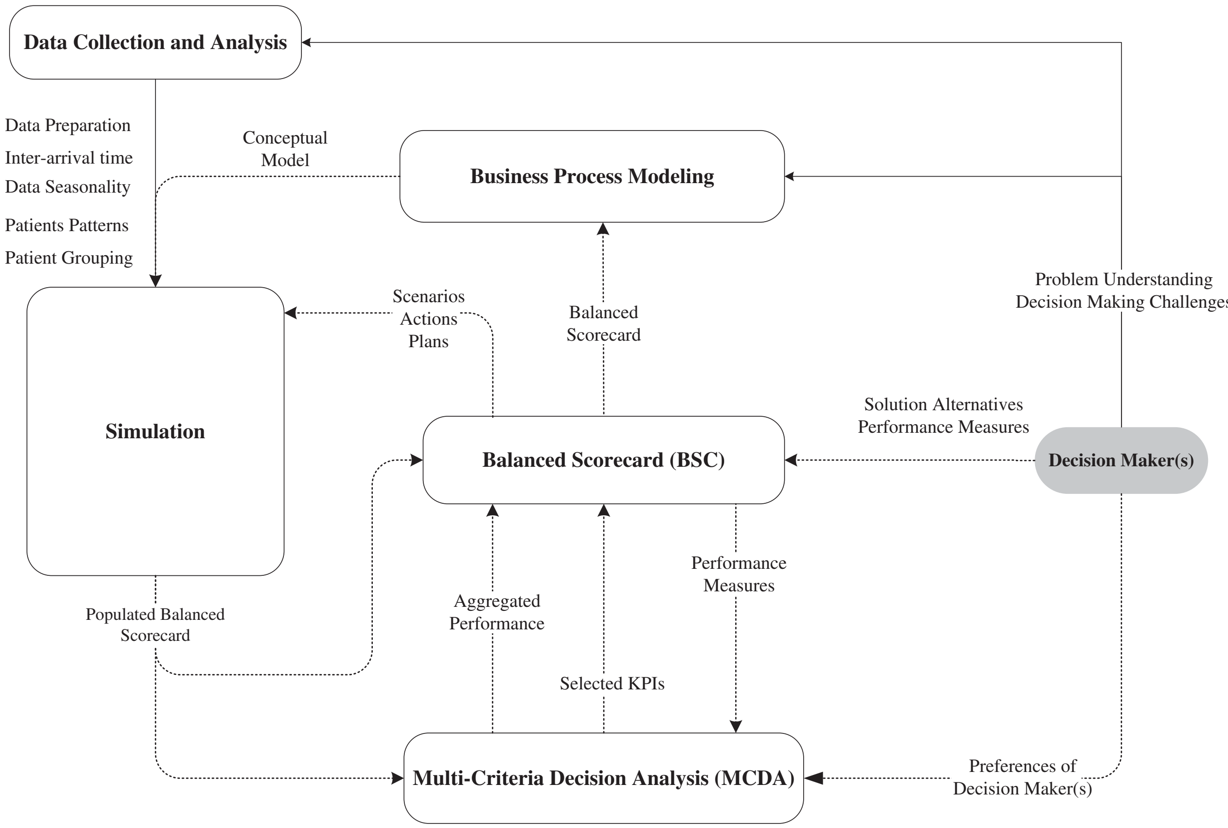

Figure 1 An overview of the integrated framework.

number of decisions and alternatives (i.e., what-if scenarios) to foresee their consequences.

Integrating BSC and simulation Although it can be applied in the context of health-care management, the full potential of the BSC cannot be realised in this context because of its limitations and the challenges involved in its implementation. In order to alleviate the BSC's limitations in terms of its measurement capabilities and its inability to identify cause-and-effect inferences between performance measures, an integration between the BSC and simulation is proposed. Performance perspectives and performance measures are collected by interviewing senior managers of health-care facilities (e.g., an ED). This step is essential to align the facility's performance measures with the strategic objectives of the national health authorities (i.e., HSE), so that the simulation model will provide quantitative values of the performance measures, and qualitative measures (such as patient satisfaction) can be related to measurable indicators (such as average waiting and LOS times). Such integration allows for the evaluation of a wide range of actions and plans based on the recommendations of national reports and surveys, which can then be evaluated in the form of *what-if* scenarios, and the results used to populate the designed BSC.

The results are then evaluated and interpreted by decision makers, who provide guidance on the implementation of suggested decision alternatives and plans, and set benchmarks of the maximum performance that can be achieved using the available resources and staffing levels. Thus, integrating simulation and the BSC helps focus efforts on strategic visions to obtain desired outcomes, assists in making better decisions, improves communication within the organisation, provides continual feedback on strategies, promotes adjustments to changes, and assists both individuals and organisations in achieving their goals and objectives – and at the same time the simulation process can provide interesting information about the cause-and-effect relationships among performance measures.

Multi-criteria decision analysis Although the BSC's measurement limitations can be resolved by integrating it with simulation, the large number of measures in the BSC delays the evaluation and analysis of the results, especially where they may be conflicting or even opposed to each other. MCDA tools can play an important role in addressing these challenges and overcoming the problems of selecting and evaluating the *key* performance measures during the design phase of the BSC. In the design phase of the BSC, MCDA methods can be applied for the selection of appropriate performance measures, and decision makers can evaluate and prioritise performance measures, which can then be illustrated in a *value tree* that represents the selected key performance indicators (KPIs). Following their selection,

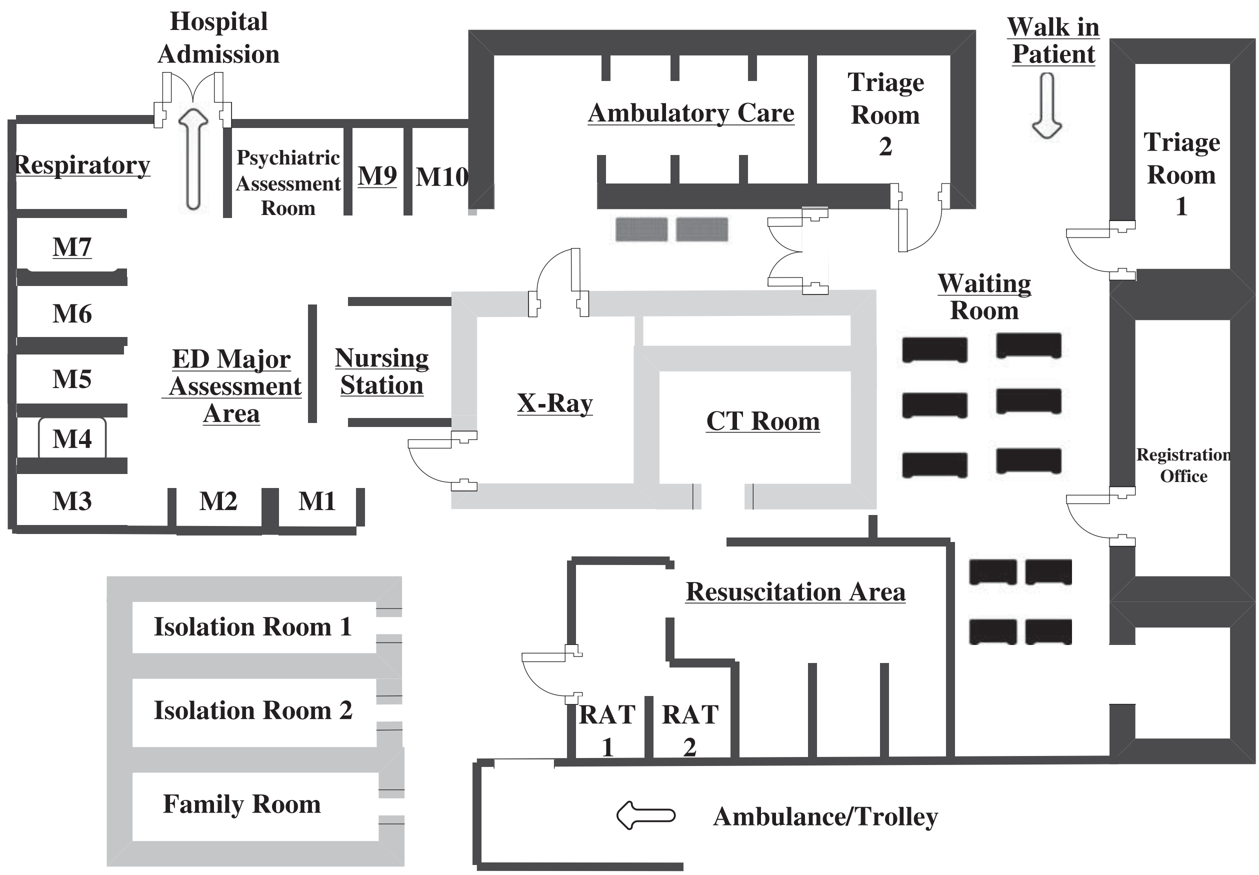

Figure 2 ED physical layout and main care areas.

the resulting value tree is passed to the simulation model. MCDA can then effectively aggregate the simulation output (i.e., KPIs) into a marginal performance according to decision makers' preferences. This dual use of MCDA within the integrated framework can contribute greatly to making informed decisions for improving and managing the health-care business process.

Framework implementation

An ED – a case study

The ED of the hospital has 13 monitored trolley spaces, 3 of which are in a resuscitation area and are reserved for major trauma and critical care patients; an ambulatory care area (capacity 6 trolley spaces); two isolation rooms; a psychiatric assessment room; two rapid assessment triage bays; and two other triage rooms. The layout of the ED is shown in Figure 2. Five distinct areas can be identified: a waiting room for walk-in patients waiting for triage, a diagnostics area (X-ray and CT scan), an ambulatory care unit (ACU) area, an ED resuscitation area (CPR), and an ED major assessment area. Patients arriving by ambulance – usually in critical condition – are routed directly to the resuscitation area, whereas patients whose conditions require monitoring stay in the major assessment area. The ambulatory care area is for patients arriving on foot, who may be suffering from abdominal pain, headache, limb problems, wounds, head injuries, facial problems, and so on.

As a 24-h department, the ED has three consultants, two nursing managers, and 11 nurses during the day and nine nurses at night, divided into six types of nurse: advanced nurse practitioners (ANPs), triage nurses, resuscitation nurses, respiratory nurses, majors/minors nurses, and health-care assistants. Physicians (excluding the three consultants who provide cover between 9 am and 5 pm (or 8 am and 8 pm) with 24/7 on-call provision) are divided into three types, registrar/specialist registrars; Senior House Officers (SHOs), and interns, and are distributed as follows when the roster allows: three registrars per day working 10-h shifts starting at 8 am, 12 pm and 10 pm; two interns working daily 8 am–5 pm shifts Monday to Friday; and 12 SHOs working fixed shifts during the day and night to keep the ED running. Therefore, the number of doctors on duty varies between two and seven, depending on the time of day or night.

Process mapping

A variety of data collection methods such as interviews, focus groups, observations, and historical data were used to develop a comprehensive conceptual model for the ED. Four preliminary interview sessions with senior managers (two ED consultants and two nursing managers) were carried out in order to gain insights about the current challenges they face in managing their department. A better understanding of health-care processes, activities, challenges, and variables was acquired with valuable insights into the challenges in the decision-making process. The interviews helped to develop significant inputs that critically supported the development and validation phases of the proposed framework. This was followed by constructing a focus group of ED doctors (one registrar and three SHOs) and nurses (a triage nurse, one ANP, and two general nurses) and a weekly meeting was scheduled for discussing issues such as general patient care paths, categories of patients and their complexities, and resource availability and capacity issues. Meanwhile, a number of visits were made to the ED (i.e., site visits) with the objective of analysing the ED layout, which reflects how resources are allocated and utilised within the ED. A high-level understanding of the journey of the patient through the ED was acquired from the initial findings of the interviews. Upon the arrival of walk-in patients (self- orGP referred), they register and wait in the waiting area to be triaged. When their name is called (depending on triage staff availability) they are generally assessed by a triage nurse. On the basis of their condition and triage assessment, each patient is assigned a clinical priority (triage category) according to the Manchester Triage System (MTS), which is widely used in the United Kingdom, Europe, and Australia (Cronin, 2003) and uses a five-level scale for classifying patients according to their care requirements: immediate, very urgent, urgent, standard, and non-urgent. Once a triage category is assigned, the patient may be sent back to the waiting room until a bed or trolley is available in an area where they can be given treatment appropriate to the type and intensity of their care needs. Waiting times for patients will depend on their triage category and the availability of both medical staff (i.e., ED physician or ANP) and empty trolleys, which are a prerequisite for full and accurate assessment. After they have been assessed by an ED clinician, a decision is made either to discharge or to admit. These are the primary care stages that apply to all patients, whether they are discharged from or admitted to hospital. Secondary patient stages are those steps that may be involved in the care of some (but not all) patients such as diagnostics (e.g., X-rays, blood tests, etc), and further ED-doctor assessment or consultation with a medical/surgical specialty doctor to confirm whether a patient should be admitted or to gain advice on the best possible treatment for a patient being discharged. Figure 3 shows a detailed flowchart for patient journey through the ED.

The developed flow charts for patient flow were effective in fast and informal process representation, and therefore they are effective in communication and discussions

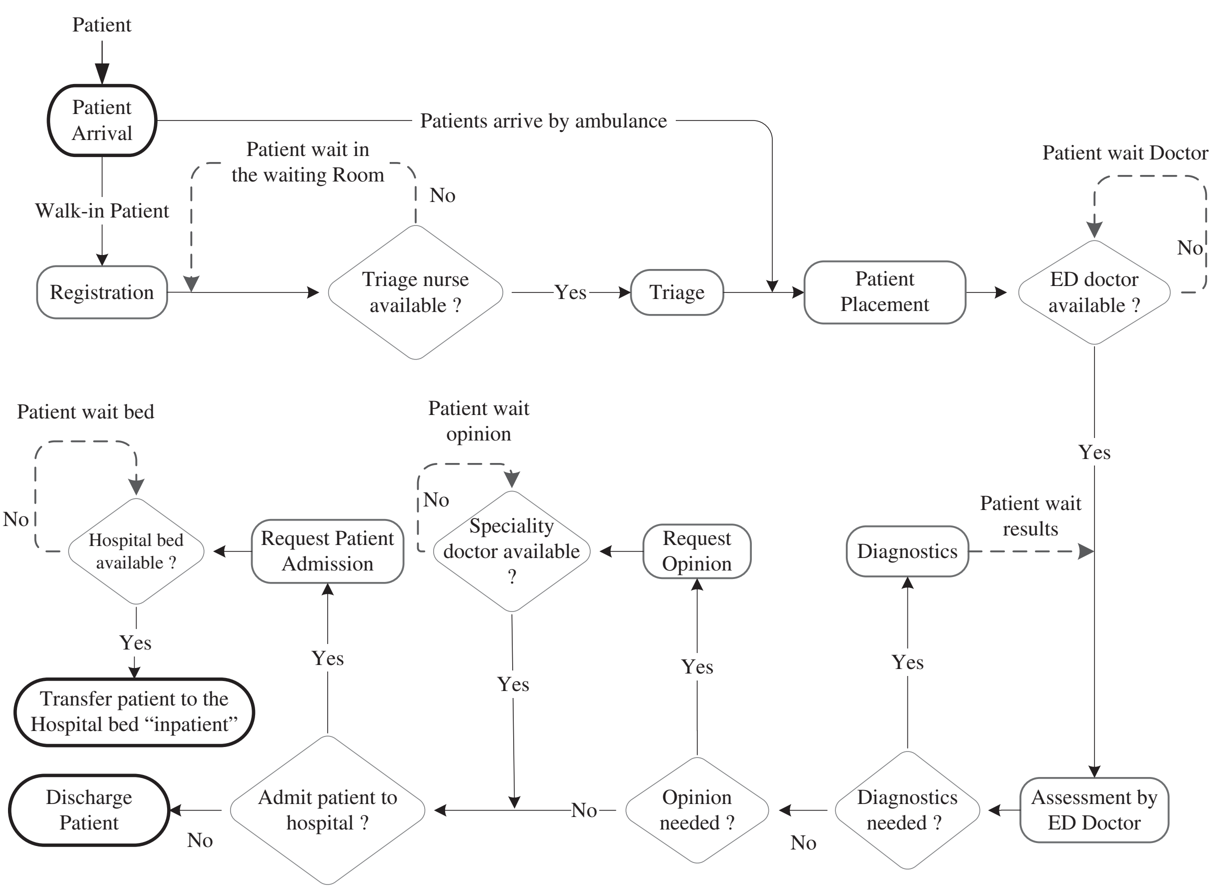

Figure 3 Detailed patient flow through the ED.

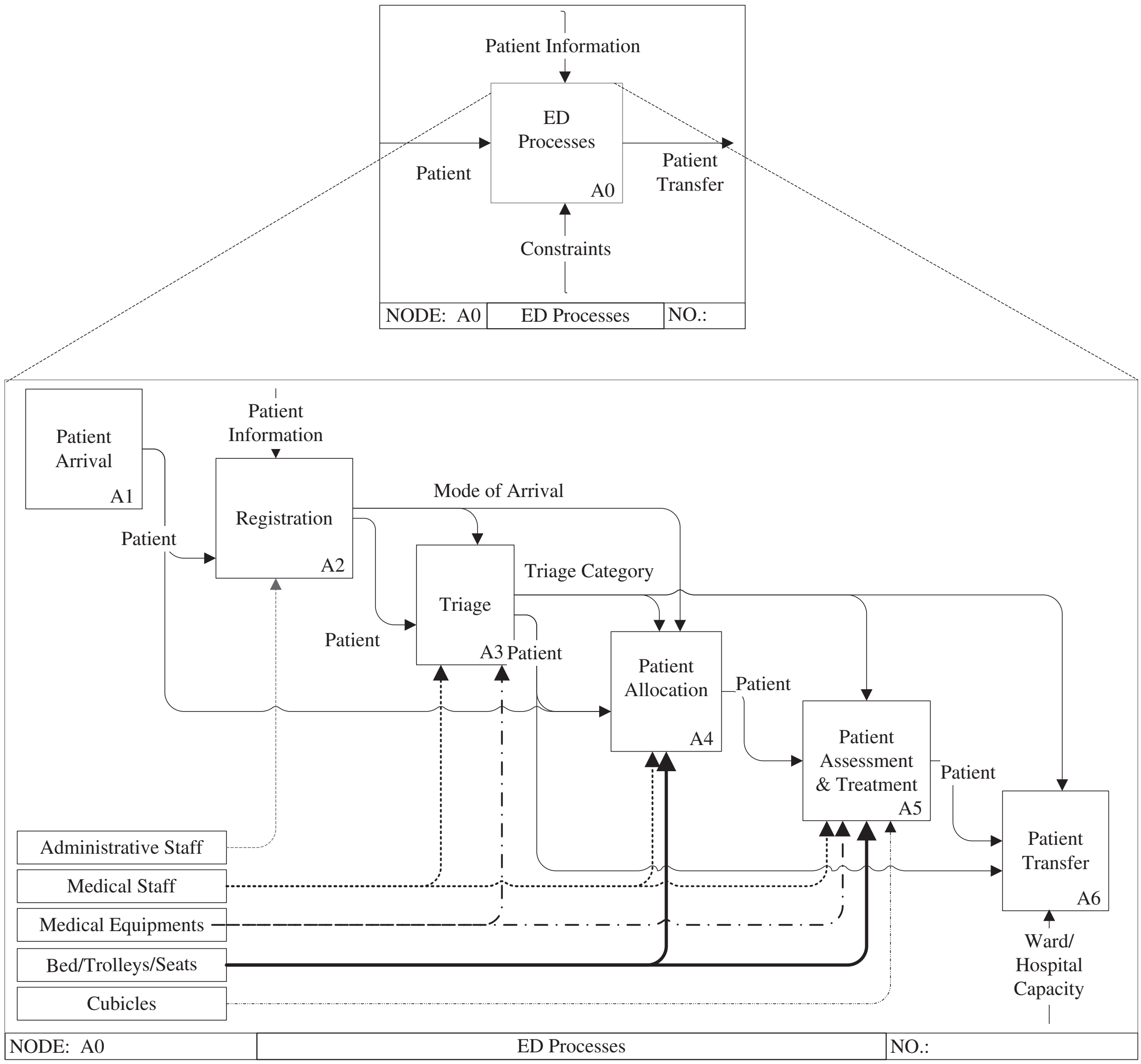

Figure 4 Mapping main ED processes.

between analysts and stakeholders. However, flowcharts use a sequential order of actions, do not support a breakdown of activities (Aguilar-Saven, 2004), and lack the necessary semantics to support more complex and standardised constructs (Havey, 2005). Therefore, different levels of detail about the patient flow were collected by the research team over a number of site visits. Site visits were carried out two times per week and different weekdays were selected at different hours (i.e., morning, afternoon, and night time). This was an essential step in order to observe the variability of care service demand (i.e., patient arrival) and to note the processes that the patient goes through. On the basis of the analysis of this stage, each ED process was broken down into smaller sub-functions, and key resources (e.g., staff and medical equipment) were identified at each care stage and detailed using IDEF0. IDEF0 is a structural graphical representation of processes or complex systems that allows the analysis and communication of the functional aspect of a system (NIST, 1993). Each process in IDEF0 is described as a combination of activities, inputs, controls, and mechanisms in a hierarchical fashion. At the highest level the representation may be of an entire process. The processes can be further decomposed to show lower-level activities. The breakdown of processes may continue until a point where sufficient detail is reached (Colquhoun *et al*, 1993). This hierarchical structure of IDEF0 keeps the model scope within the boundaries and allows the system to be easily refined into more detail until the model is as descriptive as necessary for the decision maker (Kim & Jang, 2002). The top level of the developed IDEF0 model for the ED is shown in Figure 4. The main unit of an IDEF0 model is an activity block that describes the process's main function, with ICOMs (Input, Control, Output, and Mechanism) represented by horizontal and vertical arrows. Process control (top arrow) can be patient information (e.g., arrival time, triage category, and presenting complaint), safety regulations, or national/international standards, whereas process mechanisms are usually the agents and/or physical resources that facilitate the activity (e.g., ED physicians, nurses, and beds/trolleys).

A BSC for the ED

In conjunction with the process mapping phase, a number of interviews with ED senior managers (two consultants and two nurse managers) took place to collect information about the performance areas and performance measures. Incorporating these measures at that stage was very useful for developing the BSC for the ED and setting the objectives of the simulation model. The findings of this stage resulted in the selection of four performance perspectives in the design of BSC: community, patient, internal business processes, and learning and growth. An overview of these perspectives is given in Figure 5 and brief details of performance measures in each perspective are discussed.

Community engagement perspective: This perspective brings HSE performance targets and national Emergency Medicine Program (EMP) measures into the BSC. The HSE performance target is that all patients be processed through the ED within 6 h of arriving, before 'separation' (i.e., including discharge or admission where relevant). The overarching aims of the EMP are to improve the safety and quality of patient care in EDs and to reduce waiting times for patients. In designing the ED BSC, 'patient' was selected as a sole perspective and 'patient satisfaction' as its main measure. The efficiency of internal ED processes impacts patient satisfaction levels, and therefore average patient waiting and LOS times are connected to this performance measure. The main objective in the *Internal Business Processes* perspective is to improve the ED performance in terms of its layout efficiency, ED productivity, resource utilisation, and patient throughput. The layout efficiency measures the average daily distances travelled by doctors and nurses, while the ED productivity is measured in terms of five indicators: the ratio of patients per doctor, the ratio of patients per nurse, the percentage of patients treated, the percentage of patients admitted to the hospital, and the percentage of patients who leave the ED without treatment. Resource utilisation is measured for two types of resources: ED staff and ED assets such as major trolleys, ACUs, and resuscitation rooms (CPRs).

Patient throughput is measured via three dimensions: average patient cycle times, average patient waiting times, and average patient service (processing) times. The total patient cycle time is measured across the different stages of a patient's journey in the ED such as registration, triage, treatment, and diagnostics. This includes LOS for both admitted and discharged patients. Similarly, patients' average waiting times are detailed for each stage, for example, the average wait for triage, to be seen by ED physician, and for discharge or hospital admission.

Learning and growth perspective: Two main performance measures are selected in this perspective: staff

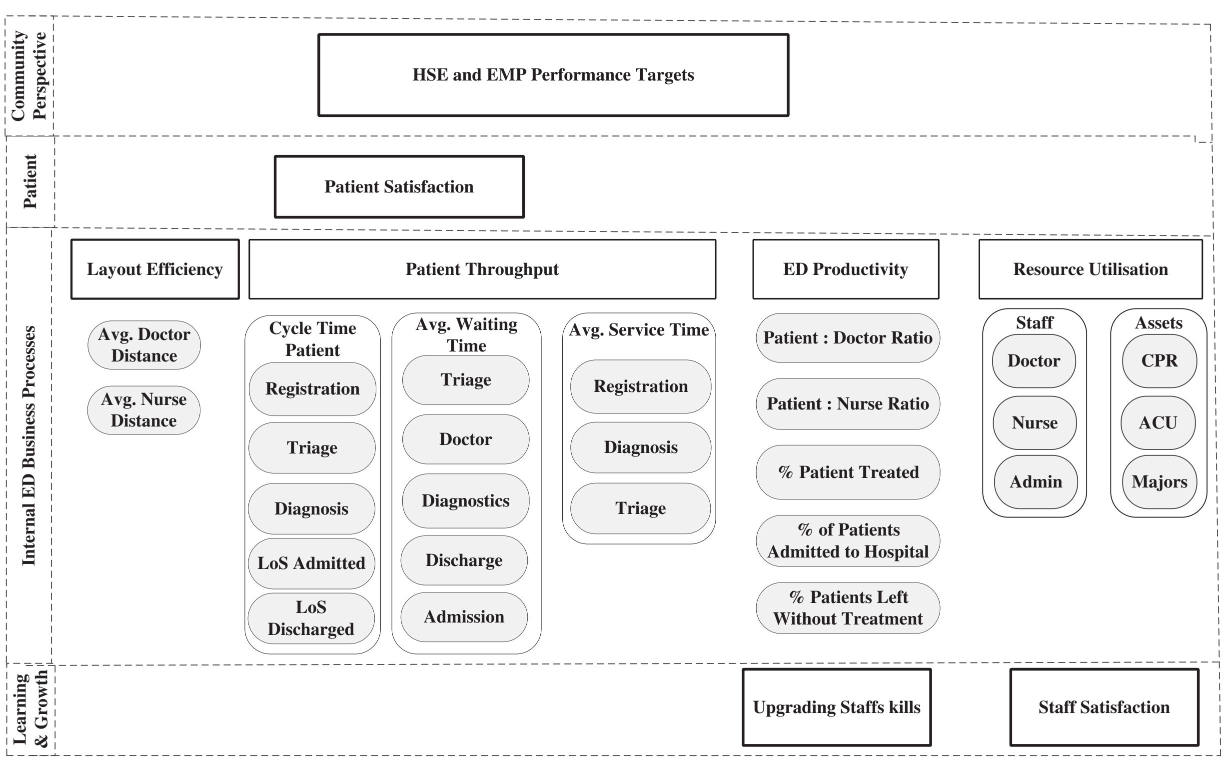

Figure 5 The ED Balanced Scorecard.

development and staff satisfaction levels. The former is measured in terms of the effect of training the staff to do more than one task so that they can be allocated dynamically within the ED. The latter is related to the 'internal ED business processes' perspective through the following indicators: staff utilisation, ratio of patients per doctor, and ratio of patients per nurse.

Data analysis

A focus group for historical data collection was formed to discuss issues related to electronic patient records, existing information systems, and data entry procedures. The focus group included members from the information system department in the partner hospital. The discussions with the focus group were supported by close observation of the data entry procedures through the patient journey and by a series of short interviews with the ED staff (e.g., registration staff, triage nurses, and physicians). A real-time patient tracking information system was used to track the patient's journey within the ED. Each patient record details the following patient-level variables: (1) the patient arrival mode, (2) the date/time the patient attended the ED, (3) the date/time of patient triage, (4) the triage category assigned to the patient, (5) the date/time the patient was seen by the doctor, (6) the medical complaint presented by the patient, and (7) whether the patient left without being seen, was discharged, or was admitted to the hospital. A total of 59,986 anonymous patient records were collected over a 16-month period. Patient records were analysed to extract quantitative information about their arrival patterns, patient groupings and allocations, and routing information. Patients were grouped based in their triage category. Table 1 summarises the analysis of patient information for each triage category along with arrival mode.

An estimated distribution of patient inter-arrivals was used to input arrival patterns for each patient group into the simulation model.

Regarding patient allocation data, Table 2 shows the analysis of the places/locations to which patients were allocated within the ED. The analysis shows that the ED staff members were unable to implement the MTS triage recommendations concerning the disposition of patients. Thus, 88% of 'Immediate' category patients were seen in the resuscitation room and 9% in the majors' cubicles, while 40% per cent of 'very urgent' patients were seen in

Table 1 Summary of the analysis of patients' records

Triage category	*Percentage of patients*	*Arrival mode*	
		Walk-in (%)	*Ambulance (%)*
IMM	1.1	5	95
VURG	16.5	40	60
URG	58	61	39
STD	23.9	81	19
NURG	0.5	72	28

Note: IMM: Immediate, VURG: Very urgent, URG: Urgent, STD: Standard, NURG: Non-urgent.

Table 2 Analysis of patient allocation within the ED

ED areas	*Triage category*				
	IMM (%)	*VURG (%)*	*URG (%)*	*STD (%)*	*NURG (%)*
Resuscitation room	88	25	2	0	0
Majors area	9	15	8	1	0
Ambulatory care unit	0	12	10	20	11
Majors chairs	0	7	6	1	1
Rapid assessment Triage	3	12	7	2	2
Waiting room	0	14	56	74	85
X-ray sub-wait area	0	15	12	4	1

Note: IMM: Immediate, VURG: Very urgent, URG: Urgent, STD: Standard, NURG: Non-urgent.

inappropriate assessment areas (e.g., ACUs). Moreover, because of the overcrowded nature of the ED, the majority of standard and non-urgent patients were assessed and treated in inappropriate areas (e.g., chairs or waiting areas).

Simulation model development and validation

A comprehensive simulation model was developed by the research team for the ED based on the ED business process model, the designed BSC, and the analysis of empirical data. The simulation model comprised a number of modules. These modules were linked together in the same way the blocks were linked in the conceptual flow chart; this facilitated the model construction phase. The top level of the simulation model defined the overall model structure and the sub-level blocks containing additional modules with greater detail. Object-oriented programming was used to customise pre-defined blocks for constructing the ED simulation model. Moreover, a relational database was used to save the measured KPIs after each simulation run, after which the populated BSC data were exported in tabular form for future analysis and validation. To reduce the time of the model development cycle and to increase the confidence of the ED simulation model results, verification and validation were carried out throughout the development phases of the model. Furthermore, each model development phase was verified and validated against the previously completed phases. The verification of the model's logic was carried out to ensure that patients in the simulation model follow the correct expected care paths; this was achieved by visually tracking patients (using animation) and checking intermediate output values such as queue lengths and waiting times between processes. The conceptual model was documented and validated by circulating it among ED senior managers and senior nursing staff, crucial steps to ensure that the logics of the model and ED activities were correct. All distributions determined from the data and used in the model were validated using the Kolmogorov–Smirnov goodness of fit test with a 5% significance level (Massey, 1951). Simulation variables

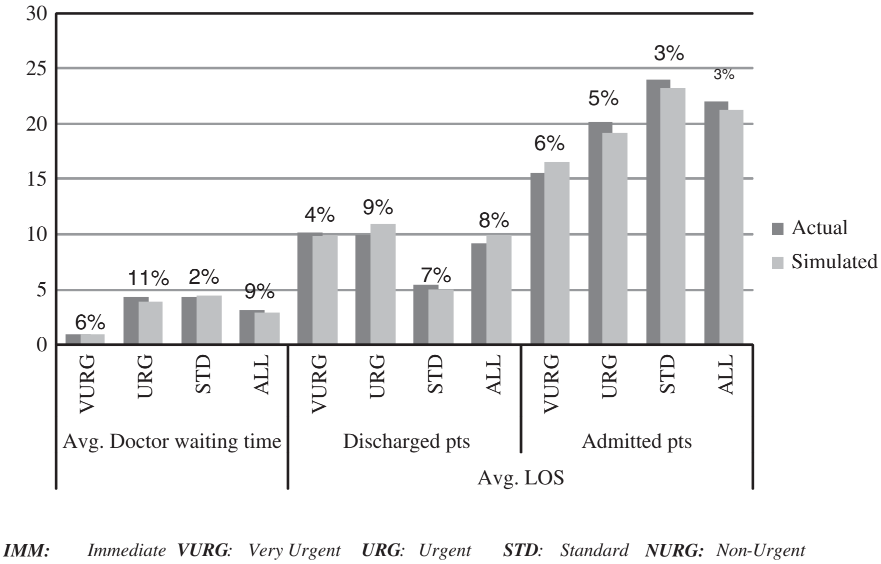

Figure 6 Validation of simulation results against actual data.

were initialised using the empirical data, the ED layout, and patient flow analysis given in previous sections. Queues at each stage of patient care (e.g., triage, seen by doctor, awaiting admission, and discharge) were set as empty and idle. A warm-up period of 2 months was found to mitigate any bias introduced by the initial conditions of the simulation model. The final results of the simulation model were validated using face validation and comparison testing. Face validation was performed by interviewing ED senior managers and nursing staff to validate the final results of the simulation model. Comparison testing involved comparing the output of the simulation model with the real output of the system under identical input conditions (Balci, 1997). Three main KPIs are used in this approach: average waiting times until seen by doctor, average LOS for discharged patients, and average LOS for admitted patients. In addition to the overall averages for all patients, detailed data for each KPI were also calculated for three triage categories: VURG, URG, and STD. On the basis of the comparison testing approach, the deviation between actual and simulated results for these KPIs ranged from 1 to 11% with an average of only 6% (Figure 6).

The comparison in Figure 6 shows that waiting times for urgent patients (URG) has the largest deviation (11%), which is reflected in the total average LOS for the same group of patients (9% for discharged patients and 5% for admitted patients). According to the ED consultants, urgent patients (who represent 60% of patients attending the ED) are the most challenging and diverse group of patients with a wide range of medical complaints and ageing conditions. The underlying assumptions used to build the simulation model have also factored in such deviation. For example, only staff activities related to direct contact with patients were considered; other routine work and break times could not be considered because of the high level of variations in these activities and lack of accurate data.

KPIs selection

The BSC developed for the ED in the previous section includes qualitative measures – such as patient satisfaction, staff skills upgrading, and staff satisfaction – as well as quantitative measures. Although these measures cannot be measured directly in the simulation, they are directly related to the quantitative performance measures in the 'Internal Business Processes' perspective, which can be directly measured in the simulation model. Nevertheless, there is a level of redundancy between the performance measures in the internal ED business process perspective – for example, 'percentage of Patients Treated' and 'percentage of Patients Leaving without Treatment' are clearly complementary. Several ED measures – such as staff utilisation and staff satisfaction – may actually conflict; thus, maximising staff utilisation may reach burnout levels (i.e., 85% utilisation), which then decreases staff satisfaction levels. Consequently, to narrow down the list of the measures and to achieve a useful trade-off between conflicting objectives, MCDA tools are used to select the main KPIs systematically.

The selection process is based on SMART (Barron & Barrett, 1996) to identify the *alternatives* and *criteria* that are relevant to the decision problem. SMART begins with identifying the alternatives (in this case, performance measures in the BSC) and specifying the criteria to be used for evaluating these alternatives. The SMART procedure is applied to the performance measures in the 'Internal ED business processes' perspective. Therefore, the 26 performance measures within this perspective are considered as the 'decision alternatives' for the SMART procedure, and are then evaluated against the main ED performance

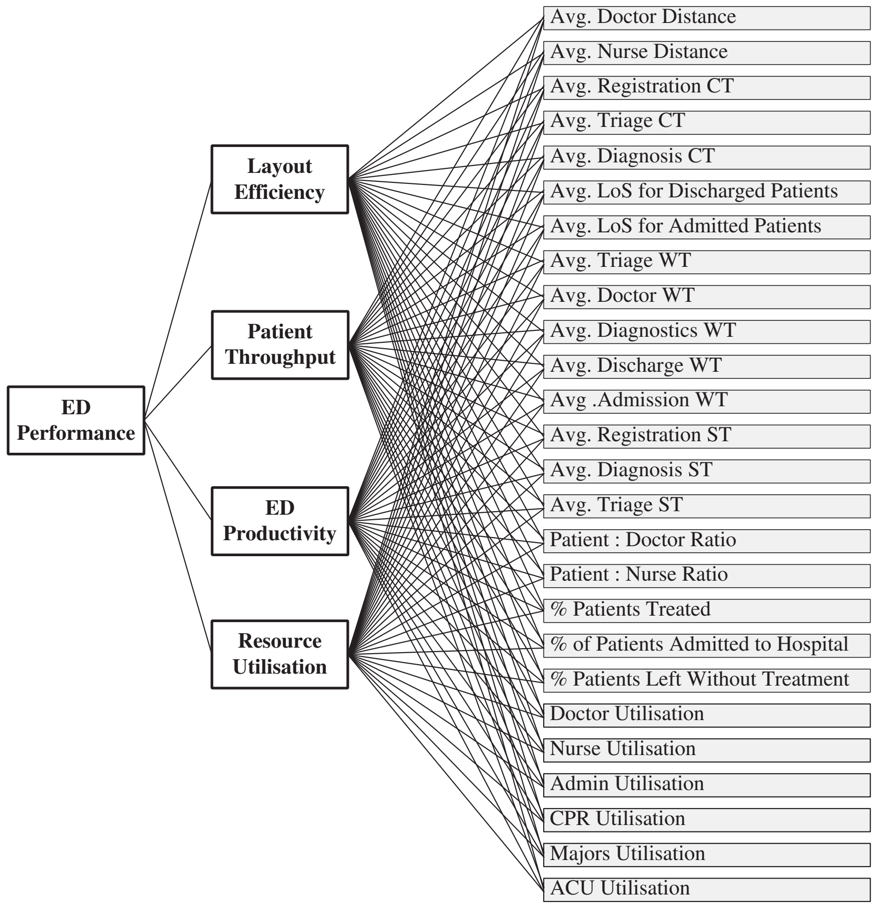

Figure 7 Alternatives value tree.

drivers, namely, layout efficiency, patient throughput, ED productivity, and resource utilisation. Once the alternatives and criteria were identified, a value tree was produced (as shown in Figure 7): the root of the tree represents the ED performance, the first level represents the evaluation criteria, and the second level represents the candidate alternatives.

The ED managers were asked to rank the alternatives with respect to each criterion in order, from the most to least preferred, on an easy-to-use value scale (Valiris *et al*, 2005). For each criterion, a value of 100 was given to the most relevant measure and 0 to the least relevant. With respect to the 'layout efficiency' criterion, for example, the 'average distance travelled by doctors' within the ED was seen as the most relevant and the 'average patient registration service time' as the least relevant. Table 3 represents preferences for each of the four main criteria where the bold values in each column are given to the most relevant measure to that column.

The remaining set of alternatives are then rated regarding the most relevant and the least relevant and assigned a value that ranges from 0 to 100. As the evaluation criteria were not of equal importance, their relative importance to the overall ED performance was ranked by the ED consultants as shown in Table 4.

The normalised weighting is calculated by dividing the 'value score' for the particular criterion by the total for all value scores, that is, for Rank 1, $100/270 = 0.37$. The total score is then calculated for each alternative as the weighted average of the value scores for all of its criteria. For example, Table 5 shows the aggregated weights and values for 'percentage of Patients Treated'.

Table 6 summarises the final weighted scores for all the alternatives and specifies the rank of each alternative.

Finally, the consultants set a cut-off level of 50 for the total score for the alternatives to highlight the most important factors and leave the others out of consideration to make the results simpler to use (Figure 8). These final sets of alternatives were then passed to the simulation model as the simulation output.

Real-time strategies for the ED

Scenario design

The main scenarios introduced involved increased clinical assessment resources (adding six extra trolley cubicles), increased availability of clinical assessors (adding one extra SHO shift at night), and absolute compliance with the national 6-h admission target (zero tolerance) (Table 7). Each scenario runs for 3-month blocks, a period identified

Table 3 ED senior managers' rating of alternatives for each criterion

Alternatives	*Evaluation criteria*			
	Layout efficiency	*Patient throughput*	*ED productivity*	*Resource utilisation*
Average doctor distance	**100**	50	70	90
Average nurse distance	90	50	70	80
Average registration CT	10	60	20	20
Average diagnosis CT	20	60	50	20
Average triage CT	20	30	50	10
Average LOS for discharged patients	30	**100**	30	70
Average LOS for admitted patients	40	90	30	70
Average triage WT	30	20	0	10
Average doctor WT	60	70	40	40
Average diagnostics WT	10	0	10	10
Average admission WT	20	20	10	20
Average discharge WT	20	10	10	0
Average registration ST	0	10	10	20
Average diagnosis ST	20	10	20	10
Average triage ST	20	10	10	20
Patient to doctor ratio	40	80	90	90
Patient to nurse ratio	40	80	80	90
Percentage of patients treated	50	90	**100**	80
Percentage of patients admitted	30	60	20	70
Percentage of patients left without treatment	20	30	30	30
Doctor utilisation	70	70	90	**100**
Nurse utilisation	70	70	90	90
Administrator utilisation	10	20	30	20
CPR trolleys utilisation	70	70	80	80
Majors trolleys utilisation	80	70	80	80
ACU trolleys utilisation	60	60	70	70

Bold value in each column refers to the most relevant measure to that column.
Note: CT: Cycle time, WT: Waiting time, ST: Service time, LOS: Length of stay.

Table 4 The relative importance of the evaluation criteria

Rank	*Criterion*	*Value score*	*Normalised weighting*
1	Patient throughput	100	0.37
2	ED productivity	80	0.29
3	Resource utilisation	60	0.22
4	Layout efficiency	30	0.11

by ED managers as being generally associated with stable ED staffing levels.

The scenarios were suggested by the ED senior managers to evaluate the proposed new hospital extension that was intended to include rebuilding of key parts of the facility including the ED. As expanding the ED capacity was likely to eventually necessitate corresponding increases in its staffing levels, hospital managers and those planning the new ED were interested in evaluating the effects of

Table 5 Aggregated weights and values for 'percentage of patients treated'

Criterion	*Value score*	*Criterion weight*	*Alternative weight*
Layout efficiency	50	0.11	5.56
Patient throughput	90	0.37	33.33
ED productivity	100	0.29	29.63
Resource utilisation	80	0.22	17.78
Total			86.30

capacity and staffing levels expansion against the effects of unblocking critical performance bottlenecks such as the 'access block' from the ED to the hospital.

Analysis of results

The results of the simulation model (see Table 8) showed that adopting Scenario 3 (absolute enforcement of the national 6-h admission target) had the most significant impact on the average LOS at every stage of patients moving through the ED. Average LOS for patients who are ultimately discharged directly from the ED decreased from 10.23 h to 5.3 h (48% improvement in LOS).

The changes that followed from the first two scenarios, namely, 'capacity expansion' and 'increasing staff', resulted in fewer improvements that were neither clinically significant nor improved patient experience (i.e., had a negligible impact on average LOS for admitted patients). The 'zero-tolerance' scenario improved how the department utilised its physicians, and was also expected to improve the average LOS of patients waiting to be admitted to the hospital.

In order to consider the preferences of the ED managers in the analysis of these scenarios, AHP was used. Table 9 presents the AHP comparison matrix for the four main ED performance criteria and their corresponding weightings.

A comparison matrix for each criterion was then constructed to obtain the weights of individual KPIs. Table 10 shows the comparison matrix for the three KPIs representing the 'Patient Throughput' criterion and their AHP weightings.

The same process of comparing pairs of KPIs for each main criterion was repeated until the last level was reached. Figure 9 shows the final weights for all the levels in the performance value tree. After calculating the relative weightings, ED managers determined the acceptable range for each KPI. For example, staff utilisation (for nurses and doctors) was given a range between 50 and 85% to avoid burnout levels (of 85%). Similarly, a range between 0 and 6 was specified for the LOS KPI to measure the levels achieved by each scenario while keeping to the 6-h maximum HSE target. After the acceptable ranges had been assigned, a value function was attached to each individual KPI to describe the desirability of achieving different performance levels.

Given the results of the simulation model reported in Table 8, and the AHP preference model in Figure 10, the

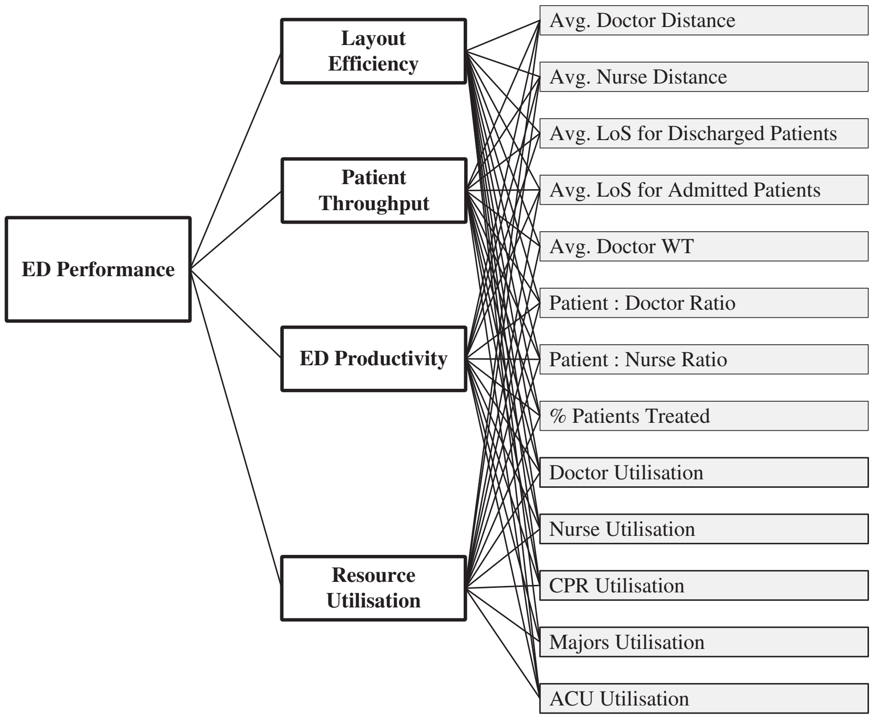

Figure 8 ED KPIs.

Table 6 Final scores and alternative rankings using SMART procedure

Alternatives	*Total score*	*Rank*	*Alternatives*	*Total score*	*Rank*
Percentage of patients treated	86.30	1	Percentage of patients admitted	47.04	14
Doctor utilisation	82.59	2	Average diagnosis CT	43.70	15
Patient to doctor ratio	80.74	3	Average registration CT	33.70	16
Nurse utilisation	80.37	4	Average triage CT	30.37	17
Patient to nurse ratio	77.78	5	Percentage of patients left without treatment	28.89	18
Majors trolleys utilisation	76.30	6	Administrator utilisation	21.85	19
CPR trolleys utilisation	75.19	7	Average admission WT	17.04	20
Average doctor distance	70.37	8	Average diagnosis ST	14.07	21
Average nurse distance	67.04	9	Average triage ST	13.33	22
ACU trolleys utilisation	65.19	10	Average triage WT	12.96	23
Average LOS for discharged patients	64.81	11	Average registration ST	11.11	24
Average LOS for admitted patients	62.22	12	Average discharge WT	8.89	25
Average doctor WT	53.33	13	Average Lab WT	6.30	26

Note: CT: Cycle time, WT: Waiting time, ST: Service time, LOS: Length of stay.

Table 7 Simulation variables for baseline system and scenarios

Scenarios	*Decision variables*		
	Access block	*Physical capacity*	*Staff*
Base line	Yes	13	—
Capacity Expansion	Yes	19	—
Increasing staff	Yes	13	1 SHO [9 pm to 7 am]
Zero tolerance	No	13	—

final value for each scenario including the baseline scenario (which was set as the current ED operation) was aggregated and summarised in Table 11.

The analysis of the AHP results showed that if the hospital implements the 'zero-tolerance' strategy this will have the most significant impact on the throughput of patients (producing 54.6% increases), and on the overall ED performance (Figure 10).

Sensitivity analysis

A one-way sensitivity analysis was conducted to explore how sensitive each decision alternative (i.e., strategy or scenario) is to variations in performance measures. In one-way sensitivity analysis, single-attribute value functions or attribute ratings for decision alternatives are varied, one at time, to see how sensitive the model is

Table 8 Simulation results of Scenarios 1, 2, and 3

Key Performance Indicators (KPIs)		*Base line*	*Capacity expansion*		*Increasing staff*		*Zero tolerance*	
			O/P	*↑↓ (%)*	*O/P*	*↑↓ (%)*	*O/P*	*↑↓ (%)*
Patient throughput	AWT doctor (h)	2.96	2.50	15	2.80	5	1.80	39
	Average LOS Dis. Pts. (h)	10.23	8.40	18	9.80	4	5.30	48
	Average LOS Adm. Pts. (h)	21.30	18.20	15	19.80	7	5.70	73
Resource utilisation	Doctor utilisation	81%	84%	4	73%	10	86%	7
	Nurse utilisation	82%	87%	7	83%	1	74%	10
	CPR utilisation	91%	86%	6	91%	0	87%	5
	Majors utilisation	94%	82%	13	92%	2	85%	10
	ACU utilisation	93%	75%	19	94%	2	83%	11
Layout efficiency	Average doctor distance (km/d)	3.24	3.63	12	2.83	13	3.91	21
	Average nurse distance (km/d)	6.48	7.32	13	6.55	1	5.34	18
ED productivity	Patient:Doctor Ratio	7.34	7.52	2	7.14	3	7.9	8
	Patient:Nurse Ratio	9.84	10.22	4	10.16	3	10.8	10
	Percentage of patients treated	83%	85%	2	90%	8	96%	16

Note: AWT: Average waiting time, LOS: Length of stay, Dis. Pts.: Discharged patients, Adm. Pts.: Admitted patients.

Table 9 AHP comparison matrix for main KPIs in ED performance criteria

	LE	*PT*	*PR*	*RU*	*Resulting AHP weight*
LE	1	0.125	0.167	0.25	0.046
PT	8	1.000	3.000	6.00	0.581
PR	6	0.330	1.000	3.00	0.285
RU	4	0.167	0.330	1.00	0.116

Note: LE: Layout efficiency, PT: Patient throughput, PR: ED productivity, RU: Resource utilisation.

Table 10 The comparison matrix for the KPIs of the patient throughput criterion

	Average LOS distance	*Average LOS administrator*	*A.W. T. doctor*	*AHP weight*
Average LOS discharged patients	1	0.33	4	0.304
Average LOS admitted patients	3	1	3	0.575
AWT doctor	0.25	0.33	1	0.121

Note: AWT: Average waiting time, LOS: Length of stay.

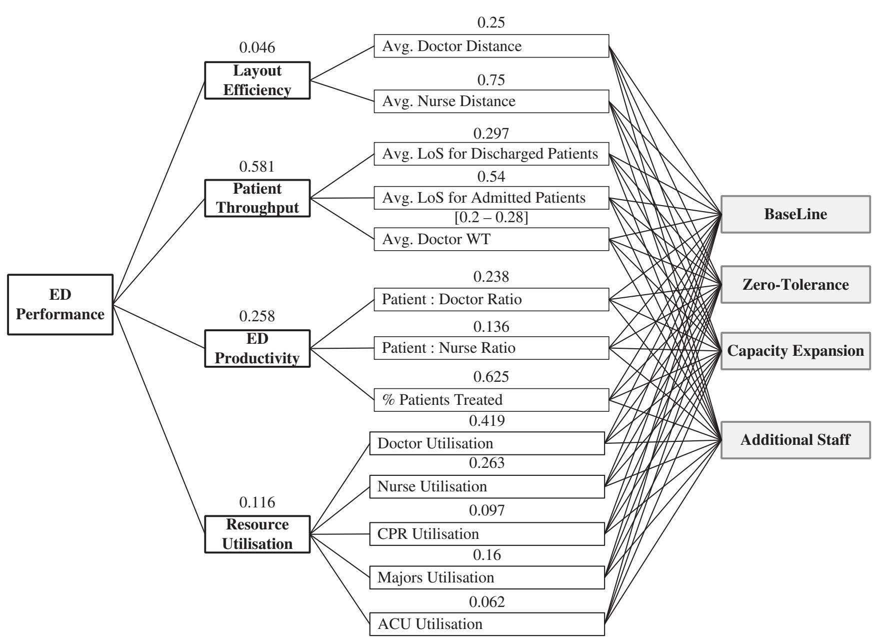

Figure 9 Full AHP weighted value tree.

to those changes. The total values of decision alternatives are drawn as a function of the variable under consideration. Figure 11 shows the sensitivity of proposed scenarios to the variation in average LOS. The zero-tolerance scenario gives the highest overall value for the ED performance. The baseline gives the lowest value among all the alternatives as the average LOS increases. The increase of the average LOS for the ED above 6 h will

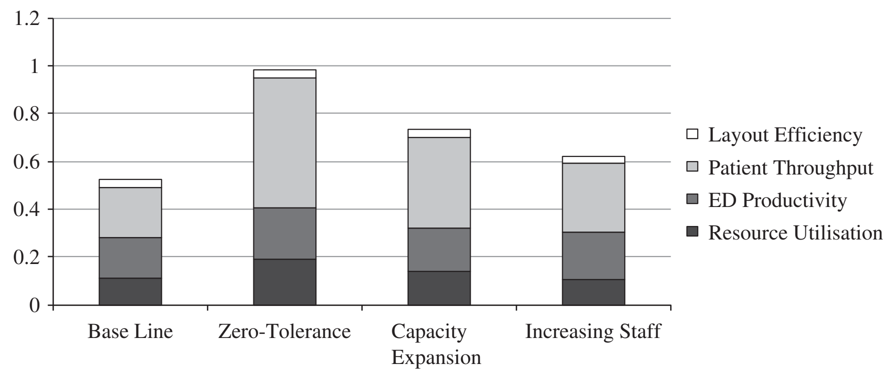

Figure 10 The ED performance for all the scenarios against the current ED.

Table 11 Weighted results for all scenarios against the baseline scenario

	Baseline	*Capacity expansion*	*Increasing staff*	*Zero-tolerance*
Resource utilisation	0.11	0.14	0.108	0.19
ED Productivity	0.169	0.18	0.194	0.215
Patient throughput	0.214	0.38	0.289	0.546
Layout efficiency	0.031	0.034	0.031	0.029
ED performance	0.524	0.734	0.622	0.98

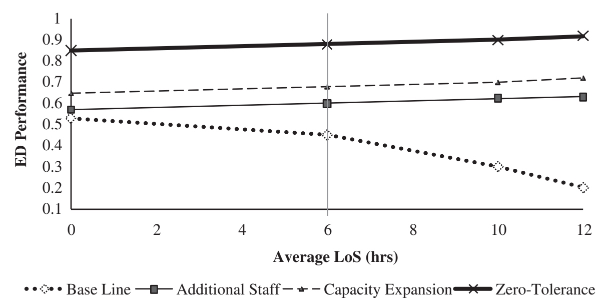

Figure 11 The change in ED performance with average LOS for all scenarios.

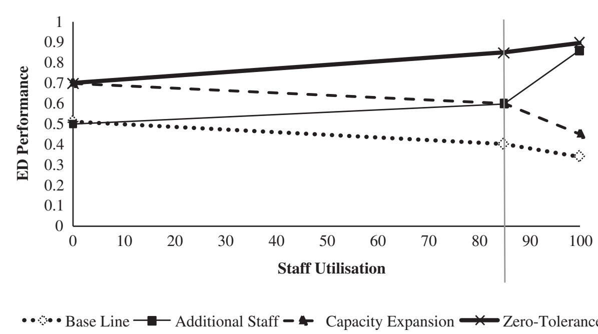

Figure 12 ED performance showing staff utilisation and burn-out levels.

deteriorate the performance of the current ED at all levels, which necessitates the addition of more staff and the expansion of the ED at this stage. However, enforcing the 6-h target (i.e., zero-tolerance scenario) outperformed these more expensive scenarios (i.e., capacity expansion and additional staff).

Similarly, the zero-tolerance scenario gives the highest overall value for the ED performance in Figure 12 when a one-way sensitivity analysis is performed for staff utilisation. If the staff utilisation is less than 85% (staff burnout level), the capacity expansion alternative is preferable to adding more staff. However, if the burnout level is reached, additional staff is recommended. On the other hand, the performance of baseline deteriorates when staff are over-utilised to the point where they reach their burnout level at 85% utilisation. The sensitivity analysis suggests that this risk can be better mitigated by increasing the ED's staffing levels than by expanding its physical capacity, which does not reduce the workload for individual staff members.

This strategy enables ED management to use their resources (e.g., physical beds and trolleys) for helping not only patients awaiting admission but also newly arrived patients. Moreover, nursing staff that are frequently monitoring patients in critical medical conditions in corridors or trolleys can be reallocated to other areas in the ED.

Therefore, the hospital management team has suggested three initiatives to implement the recommendations of this study: first, executing an escalation plan that includes placing of additional beds on inpatient wards for moving patients quickly who are waiting in the ED; second, contracting cheaper beds in community care for elderly patients – this will shorten the average LOS in the whole hospital and consequently more beds will be available for ED admissions; and finally, the hospital executives initiated lean training across all departments in the hospital. The aim of this training is to increase the coordination level between hospital units and achieve better utilisation of hospital resources. However, the implementation of these initiatives is still at its early stage and the 6-h target may or may not be achieved.

Conclusion

The proposed framework presented in this paper brought together scientists and clinicians to resolve many challenges that face health-care managers in the ED setting. Developing a detailed and comprehensive model that simulated a real process allowed managers to use a *what if* analysis approach to examine strategies and enhance their decision making.

The proposed framework has been well received by the ED managers and the hospital senior decision makers and was acknowledged as a sustainable tool to support their strategies. A number of factors have contributed to this positive perception from the management team. First, the development of a high-level process model before the development of the simulation model has greatly helped in the collection of relevant information on the operation of the system (i.e., data collection), and therefore reduced the effort and time consumed to develop the simulation model. The utilisation of IDEF for process modelling has not only improved the quality of the simulation model, but it has also enhanced the level of communication between decision makers and the staff through modelling the underlined workflow, decision points, and processes in a hierarchical form. Second, the integration between simulation modelling and BSC established a clear link between the strategic objectives of the hospital and the daily activities within the department, which gave decision makers deep insights regarding performance bottlenecks and potential corrective plans. Finally, the combination of MCDA tools along with simulation and BSC contributed significantly to the decision-making process by explicitly dealing with priorities and trade-offs between different performance measures.

The recommendations of the framework have been considered by the executive board of the partner hospital where the framework is currently used to model other hospital processes that affect the flow of patients to achieve the required alignment and coordination between hospital departments.

Although the proposed framework has successfully encompassed many factors that affect decision making, there is still room for improvement. The key limitation of the proposed framework is the cost factor of the decision. Incorporating the cost element was not possible in this study because of two main reasons: (1) lack of cost-related information to support the analysis phase and (2) the variability in the cost model in various public hospitals in Ireland created a high level of complexity in modelling the financial element. The proposed framework is also limited to Discrete-Event Simulation, and other simulation and modelling methods such as system dynamics and agent-based simulation are emerging as potential tools for analysing the interconnected relationships between health-care components at the macro-level of the system.

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