Faculteit Bedrijfseconomische Wetenschappen

master handelsingenieur in de beleidsinformatica

Masterthesis

Verhogen van de informatiewaarde van een dashboard voor een spoedgevallendienst

Martijn Bomans

Scriptie ingediend tot het behalen van de graad van master handelsingenieur in de beleidsinformatica

PROMOTOR :

dr. Niels MARTIN

COPROMOTOR :

Prof. dr. Jochen BERGS

www.uhasselt.be
Universiteit Hasselt
Campus Hasselt:
Martelarenlaan 42 | 3500 Hasselt
Campus Diepenbeek:
Agoralaan Gebouw D | 3590 Diepenbeek

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This master thesis was written during the COVID-19 crisis in 2020. This global health crisis might have had an impact on the (writing) process, the research activities and the research results that are at the basis of this thesis.

Development of a generic crowding dashboard for an emergency department

Martijn Bomans

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Abstract
***Background*:** With the rise of big data in healthcare environments, promising new opportunities for analysing and managing crowding can be used to provide nurses and physicians with valuable insights in real-time regarding emergency department (ED) crowding. Several dashboards have already been developed, but the main limitation is that they are mostly developed for the use at one specific ED.
***Aim*:** This study discusses the development of a generic dashboard providing real-time information on the status of the ED and its patients.
***Methods*:** The research is structured following the principles of design science research (DSR). The aim of DSR is to develop an artifact to solve a generic problem. Therefore, a literature review is performed to gain a deeper understanding in the current use of ED dashboards and to discover the limitations of the existing dashboards. The requirements for the dashboard were formulated based on the results of a focus group attended by representatives of five EDs in Limburg and the findings of a literature review. The dashboard is developed using the open source *Shinydashboard* package in R.
***Results*:** A dashboard is developed providing real-time information at both the overall level of the ED and at the level of individual patients. Moreover, it also includes four universally accepted crowding measures. The dashboard is demonstrated using a test dataset for Belgian EDs, transformed to an event log, and fulfils all the requirements defined by the potential end-users.
***Discussion*:** The dashboard is an improvement on the existing dashboards because its use is not limited to one specific ED. Furthermore, it improves situation awareness of the care providers by presenting real-time information at patient-level and at the level of the ED. The dashboard also provides information on the physical location of the patients in the ED and on the stage of the care process in which the patients are situated. Thus, it enables the users to quickly discover bottlenecks and crowded areas.
***Conclusion*:** The developed dashboard provides real-time information on the status of the ED enhanced with drill-down functionalities to follow the cases of individual patients. It thereby serves as a decision support tool enabling users to judge whether corrective actions are needed to avoid the negative consequences of ED crowding.

Keywords Emergency department · Crowding · Dashboard · Design science research · Generic · Situation awareness

M. Bomans
University Hasselt
Agoralaan Gebouw D, 3590 Diepenbeek
E-mail: martijn.bomans@student.uhasselt.be

1 Introduction

It is extensively described in literature and well known amongst healthcare professionals that most emergency departments are often crowded [1, 2, 3, 4]. According to the American College of Emergency Physicians "Crowding occurs when the identified need for emergency services exceeds available resources for patient care in the emergency department, hospital, or both" [5]. Recent studies have linked emergency department crowding to negative consequences for both patients (e.g., delay in timely care, decrease in satisfaction, mortality and morbidity) and care providers (e.g., work related stress and burnout) [6, 7, 8, 9, 10, 11].

The current research paradigm is focused on predicting when crowding happens and controlling the causal factors in order to prevent crowding from happening. However, the ED can be characterised by a complex adaptive system (CAS) [12, 13]. A CAS is "an entity composed of many different parts that are interconnected in a way that gives the whole capabilities that the parts don't have on their own" [14]. The problem regarding the current research paradigm is that the behaviour of such complex adaptive systems is very difficult to control or predict [15]. Therefore, Bergs *et al.* [15] suggest to alter the research paradigm to analysing and managing. Here, analysing refers to the use of continuously gathered data. The rise of big data in healthcare environments creates promising new opportunities for analysing and managing crowding. The use of information and communication technology tools, electronic patient tracking, electronic health records, and so on, has caused a rapid increase in the amount of available data related to occupancy levels, waiting times, measures and indicators [16]. On the other hand, managing refers to proactive management of the system in order to prevent devastating "avalanches" [15]. This means that instead of waiting until the ED is crowded, indicators should be recognised and managed accordingly to prevent situations of poorer care quality. Several dashboards have already been developed to visualise this type of information. However, these dashboards have several shortcomings such as that they often provide information in a tabular format, which is not the most effective format of information visualisation [17] and that they are often specifically developed for one hospital which limits the generalisability [18, 19, 20, 21, 22, 23]. Moreover, some of the existing dashboards only provide information at patient- or at system level, limiting situation awareness [24]. Other shortcomings of the existing dashboards are presented in table A1 in appendix A.

The goal of this study is to develop a generic crowding dashboard for emergency departments that will enable the staff of the ED to proactively make decisions regarding possible actions to control for crowding. This dashboard will provide the ED staff with real-time information regarding individual patients as well as an aggregate overview of the emergency department as a whole. This will enable users to quickly capture the overall status of the ED and to drill down to specific patients. This way, bottlenecks can easily be detected and the patients causing them or who are affected by them can quickly be located. In order to increase the applicability, the dashboard will be generic such that it can be implemented in more than one ED. This is done by limiting the use of hospital specific details. Moreover, the dashboard was developed based on the results of a focus group attended by representatives of five EDs and the findings of the consulted literature. This ensures that the indicators included in the dashboard are relevant for more than one ED. The dashboard will also be freely available (open source) such that it is accessible for every interested ED.

The remainder of this paper is structured as follows. Section two outlines the research questions and the methodology. The third section discusses key related work. In the fourth section the development, demonstration and evaluation of the dashboard is described, guided by the design science research framework of Johannesson and Perjons [25]. In the fifth section, the findings of this study are discussed. In the last section, a conclusion is formulated based on the findings of the study. Lastly, the content of the developed dashboard is described in appendix A.

2 Research questions and methodology

2.1 Research questions

The goal of this study is the development of a generic dashboard that provides real-time information regarding ED crowding. Therefore, it needs to be investigated which dashboards already exist for this purpose and what their main limitations are, to create a new state of the art crowding dashboard.

To this end, four research questions were formulated that will guide the search for relevant articles.

1. Which crowding dashboards exist and what is their purpose?

1. Which are the most commonly used dashboards in emergency departments?

2. Which are the most common shortcomings of dashboards used in emergency departments?

3. What are the effects of the introduction of electronic dashboards in emergency departments?

4. Which are the most important requirements of dashboards used in emergency departments?

5. Which universally accepted crowding measures exist?

2.2 Methodology

The measures and indicators that should be included in the dashboard were formulated based on the results of a focus group attended by representatives of five EDs from Limburg and based on the findings of the consulted literature. By involving the end-users, the relevance of the indicators visualised in the dashboard are based on information needs experienced in practice. During the focus group, the goal of the study was defined before the end-users were invited to provide input regarding the requirements for the dashboard.

2.2.1 Design science research

This study of developing a generic crowding dashboard for emergency departments follows the principles of design science research (DSR). DSR is a special form of design research in the area of information systems and IT with he aim of creating new artifacts in the form of models, methods and systems to support people in the development, use and maintaining of IT solutions to solve generic problems experienced in practice. DSR differs from empirical research in that it does not only describes, explains and predict but also changes the world by developing artifacts that help people fulfil their needs and overcome their problems. For more detailed information regarding DSR, the reader is referred to e.g., Johannesson and Perjons [25], Peffers *et al.* [26] and Hevner *et al.* [27]. For this study, the artifact refers to a generic dashboard developed to provide care providers with a tool to proactively make decisions in order to manage the level of crowding. Several different frameworks have been proposed in literature outlining the key activities that need to be carried out when performing DSR. Given the elaborate explanation, clear structure and intuitive use, the framework of Johannesson and perjons [25], which is based on the work of Peffers *et al.* [26], is applied in this study. In this framework, five activities are outlined: (i) explicate the problem, (ii) define requirements, (iii) design and develop artifact, (iv) demonstrate artifact, (v) evaluate artifact. The five activities are briefly explained in the context of this study.

Firstly, the practical problem needs to be investigated, analyzed, formulated and its global significance must be justified. Therefore, a literature review was performed based on the aforementioned research questions. The results of the review can be found in section 3. In order to shift the focus to analyzing an managing the ED, as stated in the introduction, real-time information on crowding is required. Crowding is not an isolated problem in only one ED, but in fact is a global problem [1, 2, 3, 4]. Therefore, the dashboard developed in this study is generic in order to be available as a global tool that can be implemented in more than one ED.

Secondly, the artifact to be designed is defined and its requirements are formulated, which is discussed in section 4.1. The artifact created in this study is a dashboard providing real-time detailed patient information, aggregate patient statistics and a set of crowding indicators. The list of desired measures and indicators was based on the input provided by representatives of five emergency departments in Limburg during a focus group and on the findings of the literature review.

Thirdly, the artifact is designed and developed, as discussed in section 4.2. Several concept versions of the dashboard were designed on paper and the final concept was evaluated by representatives for the end-users. The dashboard is created in R [28] using the *shinydashboard* package [29]. R is a programming language and open source software environment suited for statistical computing, data manipulation , data analysis and the creation of graphics [30]. *Shiny* [31] is an open source package of R providing the functionality to build interactive web applications enabling users to visualise their analyses. *Shinydashboard* provides a theme on top of the *Shiny* package focusing on the creation of dashboards [32].

Fourthly, the artifact is applied in a real-life context using data from a test dataset for Belgian EDs in order to demonstrate the feasibility of the dashboard and to show its functionalities. The dataset contains anonymised patient information. It also contains the age and gender of the patient and also medical information such as first triage code, last triage code, allocated unit and destination of patient after leaving the emergency department. Furthermore dates and times are collected for: arrival at the ED; timestamp when the triage code is given; timestamp when patient is moved from waiting room to another physical location; the request for medical imaging; execution of medical imaging; delivery of report of medical imaging; the request of lab test; execution of lab test; delivery of lab result; request for bed; time at which a bed is assigned to patient; time at which a patient leaves the ED; start of treatment (based on electronic medical cabinet information). Besides times for specific activities, the data is manually imputed with patient locations to show intended location-specific functionalities of the dashboard. The demonstration is discussed in section 4.3.

Finally, the artifact is evaluated to determine how well the artifact fulfils the requirements formulated by the end-users. The evaluation is discussed in section 4.4.

2.2.2 Research methodology

Search terms and databases This paragraph discusses the search terms and databases used to find the literature to answer the research questions. To compile a reliable base of articles, only research papers were considered. The collection of references was build from

Keywords	Google Scholar	Hasselt University Library	PubMed
((“Emergency Department management” OR “ED management”)) AND (“dashboard”) AND ((“Crowding” OR “Overcrowding”))	59	19	1
((“Emergency Department” OR “ED”)) AND ((“crowding”OR“overcrowding”)) AND (“Dashboard”)	2190	256	7
((“Emergency Department” OR “ED”)) AND (“Key Performance Indicators”) AND (“Dashboard”) AND ((“Crowding” OR “Overcrowding”))	110	31	1
((“Emergency Department” OR “ED”)) AND ((“Crowding metrics” OR “Overcrowding Metrics”))	283	134	14
((“Emergency Department” OR “ED”)) AND (“Patient Flow”) AND (“Dashboard”) AND ((“Crowding”OR“Overcrowding”))	281	93	2
Totals	2923	533	25
Total = 3481			

Table 1
Keywords

searches in three different databases namely, Google Scholar, PubMed and Hasselt University Library, using a combinations of keywords as shown in table 1. The list of keywords was partially compiled based on an initial reading of published work in the domain [15, 33, 34, 35]. Next, the list was completed by contemplating on possible keywords that could be used to solve the research questions and based on scoping searches, i.e. brief searches of existing literature based on a limited number of terms to help gain an overview of the range and depth of the research that exists [36]. Google Scholar was chosen as a database because it provides a simple platform to perform a broad search across many disciplines and sources [37]. The second database, PubMed, was chosen because it mainly contains articles from the domain of healthcare [38]. The Hasselt University Library was chosen because it enables users to search through multiple information sources in one search request [39].

In the Hasselt University Library, results were filtered on “journal article”, “conference proceedings” and “publication”.

Search process The search process was divided in three parts as shown in figure 1.

In the first part, the articles were collected as a result of the searches in the three databases using the aforementioned keywords. Table 1 contains the number of articles found for each keyword in each database. This first step resulted in a large base of 3481 potential articles.

Every title was screened to look for articles for which minimum one keyword from table 1 was present in the title. Articles resulting from the initial search without a search term in the title but with comparable words (e.g., “data-driven”, “business intelligence”) were also considered. The result of this step was a subset of 73 articles: 51 from Google Scholar, 18 from the Hasselt University Library and 4 from PubMed. Subsequently, all duplicates were discarded so only 51 articles remained.

During the second stage of the search process, the abstracts of the 51 articles were screened. Based on the abstract, the inclusion and exclusion criteria were tested to only retain the most relevant articles. Of the 51 remaining articles after stage one, 31 were discarded based on the inclusion and exclusion criteria leaving a selection of 20 articles.

The third and final part of the search process was a search through backward searching, i.e. searching and screening the references cited in an article [40]. This was done to acquire more articles based on the articles that resulted from the first two stages of the search process. Potentially interesting references were compiled in a list if the title contained one or more keywords. Next, duplicate articles were removed. Afterwards the abstracts were read and tested based on the inclusion and exclusion criteria. During this stage 31 extra articles were found. This stage concluded the search process resulting in a final selection of 51 articles.

Inclusion criteria Following are the inclusion criteria to add articles to the study:

1. The articles must be fully available.
2. Only articles in Dutch or English are used.
3. The title or the abstract must contain minimum one keyword.

Exclusion criteria Following are the exclusion criteria to discard articles from the study:

1. Articles from before the year 2000 are discarded keeping in mind the changes in information technology around the turn of the century.

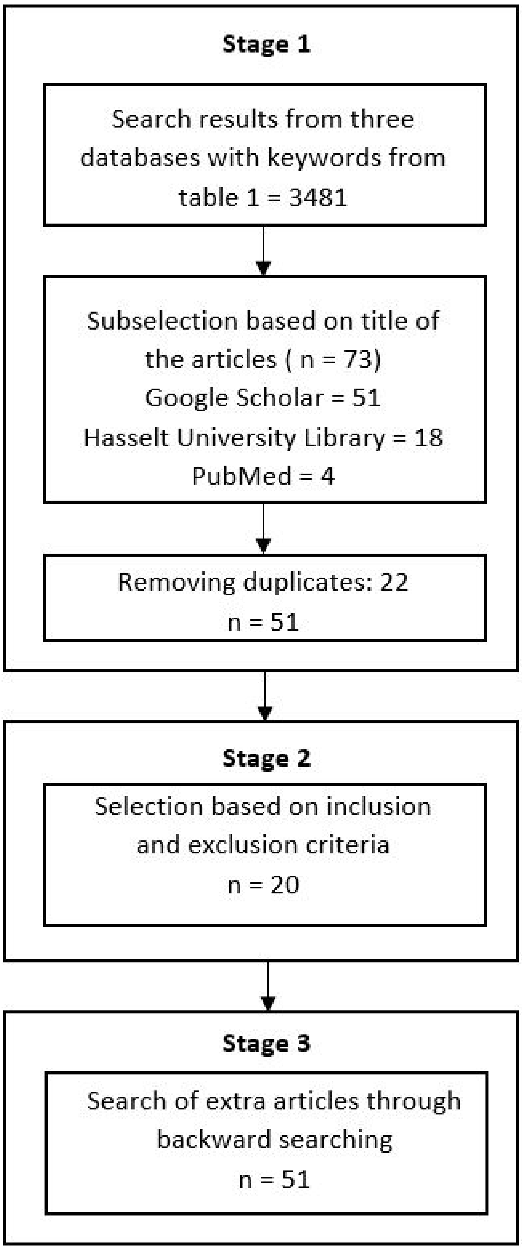

Fig. 1: Search process
n = number of articles remaining

2. Articles in the form of abstracts or tutorials are discarded.

3 Related work

Emergency departments are complex adaptive systems where data is continuously gathered. Insights from this data should be communicated to the staff to improve their decision-making in order to make rapid, proactive interventions [24, 33, 41, 42]. Therefore, emergency departments use some kind of whiteboard or dashboard for their operational management and handling of patient trajectories [43]. Originally, emergency departments used dry-erase whiteboards placed centrally in the ED to keep all staff members up to date. However, several shortcoming arise with the use of dry-erase whiteboards. These whiteboards can become complex and busy [17]. Data is permanently lost once it is deleted [24, 43, 44, 45, 46], data is not provided in real-time [24, 43], integration with other systems is not possible [24, 43, 44, 47] and drill-down functionalities are limited [47]. To overcome these shortcomings, many EDs are replacing their dry-erase whiteboards by computerised dashboards that provide information through enhanced visualizations in real-time [17, 42, 44, 46, 48].

The overview of related work is structured using the aforementioned research questions. The first part of the review discusses existing dashboards used in the ED. The second part outlines the effects and consequences of the use of electronic dashboards in the ED. Thirdly, the shortcomings of the currently used dashboards found in literature are discussed. Next, the requirements are discussed. Lastly, the universally accepted crowding measures are discussed.

3.1 Existing ED dashboards

Several ED dashboards have already been developed as shown in table A1 in appendix A. Most of these dashboards have the same type of information content, i.e. they provide (near) real-time patient information and/or key performance indicators (KPIs) to enable the users to proactively judge whether corrective actions are needed. Most dashboards also provide an overview made out of summary statistics to present a clear view of the current situation in the ED. Others provide only historical data over a larger period of time. In general, there are two types of dashboards: operational dashboards and performance dashboards. Most of the dashboards in table A1 are operational dashboards serving as a decision support tool providing real-time information. These dashboards provide visual representations in near real-time. The use of this type of dashboard is particularly crucial to healthcare because it prompts management to respond to

Dashboard	Aim
Martin et al. [33]	Provide real-time information regarding ED crowding.
Franklin et al. [24]	Create a tool providing real-time decision support by improving situation awareness. It visualises the movement of patients through the care process and enables management of flow and demands of the entire ED.
Yoo et al. [18]	Provide visualisations of ED processes. Although main goal was not directly related to ED crowding, the measures were chosen and categorised based on a conceptual model of ED crowding.
Mazor et al. [19]	Development of a dashboard to provide ED staff with information regarding bottlenecks in the care process which cause waiting with the aim of bringing down the length of stay(LOS). Overall goal: address the global problem of overcrowding by decreasing the LOS.
Lee et al. [20]	Provide electronic health record data effectively and intuitively for all ED units.
Badgeley et al. [52]	Development of a prototype clinical dashboard to integrate high-frequency health and wellness datastreams using real-time data visualisations.
Aronsky et al. [43]	Development of an ED dashboard that provides relevant operational and patient-related information in real-time to support patient care.
Wong et al. [22]	Development of an ED dashboard providing a view of current patient activity in ED units.
Hertzum and Simonsen [53], IMATIS Visi dashboard [51]	ED dashboard for resource and patient management.

Table 2
Purpose of existing dashboards

the changing needs of units within the ED, which ultimately affects its quality of care [49]. On the other hand, performance dashboards are used in specific time intervals (e.g., weekly, monthly) or after the implementation of process changes. They present important information about strategic objectives attainment enabling managers to measure, monitor, and manage performance more effectively. Furthermore, they enable managers to identify problematic areas that need corrective actions, analyze root causes of poor performance, forecast trends, and establish benchmarks [50].

Table A1 contains nine existing dashboards. The goals of these dashboards are shown in table 2. Only two of the dashboards are developed with the main purpose of visualising ED crowding [19, 33]. But some of the dashboards are developed keeping ED crowding in mind, i.e. Yoo *et al.* [18] selected measures based on a conceptual model of crowding and the dashboard of Franklin *et al.* [24] contains the NEDOCS score to indicate overcrowding. Two dashboards were mainly developed for patient management [22, 51], providing a table with one row for each patient in the ED, enabling users to follow the cases of the patients. The dashboard designed by Aronsky *et al.* [43] has the aim of improving patient care. The dashboard of Lee *et al.* [20] visualises all electronic health record information. Lastly, the dashboard of Badgeley *et al.* [52] visualises health and wellness datastreams for intended use by both physicians and patients.

3.1.1 Operational dashboards

As mentioned above, most of the dashboards used in EDs are operational dashboards. They provide real-time, or near real-time, information with the goal of aiding clinicians to proactively manage the ED [18, 19, 20, 22, 24, 33, 43, 52, 53]. Some dashboards only show summarised statistics regarding the overall state of the ED [33], some provide information only at patient-level [22, 53] and most of them provide both detailed as well as aggregate information [18, 19, 20, 24, 43, 52].

Patient-level Dashboards that only provide information at patient-level often use a tabular format where one row represents one room [22] or one patient [53]. The former uses one row for each room in the ED or hospital, regardless of whether the room is occupied or not. A column is used to indicate whether a room is empty. The other columns present information about the patient in the room (e.g., name, attending nurse, attending doctor). The latter uses one row for each patient present in the ED. Here, the columns also provide information about the patient, including in which location he or she is situated. The main problem with these dashboards is the inability to maintain an awareness of the overall state of the ED. A loss of situation awareness can occur when it is difficult for the clinicians to continuously monitor the state of the department when the dashboard does not provide insights on the overall state of the ED [24]. Therefore, with regards to developing a dashboard to manage crowding, it is not sufficient to only visualise information at patient-level.

Overall ED summary The electronic dashboard developed by Martin *et al.* [33] presents summarised statistics of the overall ED to enable care providers "to proactively judge whether corrective actions are required". Here, a loss of situation awareness can also arise because of the difficulty of monitoring the status of individual patients [24]. This is the same disadvantage as with dashboards that only provide information at patient-level. The difference is that with the use of dashboards that only provide information at system level, the clinicians do get an understanding of the status of the overall ED, but it is hard to follow the process of individual patients. On the other hand, using the dashboards that only provide information at patient-level, physicians are enabled to follow individual patients, but it is harder to get an understanding of the overall status of the ED.

Combination Providing information both at patient-level and at the level of the overall ED, enables the clinicians to take actions both for individual patients (e.g., a discussion with bed control regarding the status of a requested bed) and for the ED as a whole (e.g., redirection of nurses and doctors, such as adding nurses to the laboratory to help fasten the process) [24]. It also enables users to locate bottlenecks or crowded areas in the ED and pinpoint specific patients who contribute to these problems or suffer as a result of them [24]. Franklin *et al.* [24] suggest that providing the status of the overall ED and the status of each patient allows clinicians to make more appropriate decisions.

The dashboard developed in this study therefore provides an overview of the overall state of the ED, an overview of the patients present in the ED and functionalities to drill down from aggregate information to patient-level information. This will enable the users to quickly capture and understand the overall status of the ED to support corrective actions for the ED as a whole. Furthermore, it will enable the nurses and physicians to follow the cases of certain patients and enable them to take actions for individual patients situated in bottlenecks or for whom certain care thresholds are (almost) exceeded.

3.1.2 Performance dashboards

The other type of crowding dashboards used, are performance dashboards, i.e. they are used for planning purposes or for evaluating process improvements. The ED Dashboard and Reporting Application developed by Stone-Griffith *et al.* [35] is a performance dashboard providing five measures: arrival time, triage time, time patient was place in a bed, patient consultation time and the time that patient leaves the ED. Through continuous measurement of the entire ED throughput, deficiencies in the current processes could be exposed. The dashboard itself was not an improvement tool, rather it served as a tool to identify the problematic areas and assess the effectiveness of the implemented process changes. The dashboards developed by Staib *et al.* [54] and Martinez *et al.* [55] have the same purpose. Both dashboards are used to evaluate the effect of implemented process changes. The former dashboard consists of three types of measures: mortality rates, information regarding access to emergency care (e.g., NEAT compliance) and safety measures (e.g., Rapid Response Team activations of admission and cardiac arrest rate within 24 hours). The latter has three pages. The first page contains summary statistics over time (e.g., occupancy level, median boarding times), the second page contains KPIs regarding hospital dynamics over time (e.g., patient handoff and patient departure) and the last page provides graphs and tables to facilitate evaluations of process improvements (e.g., discharge distributions). The systems created by Stone-Griffith *et al.* [35] and Staib *et al.* [54] could provide information in near real-time although they are not intended as operational dashboards. On the other hand, the dashboard of Martinez *et al.* [55] is only used in weekly meetings or in meetings to evaluate process improvement initiatives. The dashboard "was not intended to be real-time but rather to promote retrospective evaluation by displaying longitudinal information of hospital operational performance" [55]. The dashboard developed by van Deen *et al.* [21] serves as a performance feedback dashboard and also reports in monthly intervals. The dashboard contains three pages. The first page shows the physician's individual performance (e.g., number of patients seen in total, patients per shift last month, decision time per patient) compared to others. The second page shows the performance of the ED overall as reference (e.g., total number of patients, average length of stay). The third page displays the favorite measures selected by the individual users. Lastly, Pestana *et al.* [23] suggest the use of a dashboard to achieve a more efficient allocation of resources. This dashboard presents monthly and yearly key performance indicators (e.g., yearly average delays, number of outgoing patients per year) and targets (e.g., the annual target of external appointments) to monitor the productivity of the ED.

3.2 Desirable and undesirable effects of the use of dashboards

The introduction of electronic dashboards in the EDs has led to positive effects but also to some negative effects, as shown in table 3.

Patient throughput Shen and Lee [56] suggest that the use of a data-driven approach can bring down *wait time to consultation* because the insights gathered from the data allows the users to make quick and informed decisions. The use of data analytics also enabled users to identify patterns in patient arrival times and allowed them to match the manpower in the ED to periods of surge [56].

Patient care and satisfaction According to Boger [57], electronic dashboards have also been shown to affect patient care. The introduction of an electronic dashboard at the respective hospital of this study enabled the clinicians to prioritise and manage their own time more effectively. This led to a decrease in the length of stay, a decrease in the number of patients who left without being seen and an increase in general patient satisfaction. Other recent studies on the use dashboards in the ED also reported their potential to improve patient safety, situation awareness and workflow [18, 24, 58].

Electronic dashboards could improve patient care by enhancing situation awareness of the ED staff. This can be achieved by displaying the state of individual patients as well as an overview of the state of the entire ED [59, 60]. The combination of this improved situation awareness with human-based interventions such as crew resource management then led to improved efficiency, thereby improving patient outcomes [60]. Electronic dashboards can also improve the quality of care and efficiency by sending reminders to users (e.g., when a lab report is finished) [61]. The introduction of electronic dashboards, which provide constant access to information, can also improve clinicians' adherence to quality guidelines, thereby also improving patient outcomes [42]. Moreover, work flows are also optimised when real-time information allows clinicians to make timely informed decisions and have the capacity to efficiently use the information [62]. The use of an integrated electronic dashboard that alerts radiologists to sign reports has proven to effectively decrease radiology report turnaround times [62]. Lastly, Abujudeh *et al.* [63], France *et al.* [60] and Bardram *et al.* [64] found that the quality of care can also be improved by the introduction of the electronic dashboard because it reduces the rate of interruptions and unnecessary communications.

Integration Another advantage of the introduction of electronic dashboards is the possibility of integration with other clinical and non-clinical systems such as bed tracking systems, computerized provider order entry systems and billing systems [61]. This enables clinicians to get a view of all the activities in the ED.

Communication Regarding communications and coordination of work, recent studies provide mixed findings. Abujudeh *et al.* [63], Aronsky *et al.* [43], France *et al.* [60] and Wong *et al.* [22] conclude that communications are improved with the introduction of electronic dashboards, while Ash *at al.* [65], Pennathur *et al.* [66] and Wears *et al.* [41] conclude the opposite.

Providing information in real-time improves communications because miscommunications are limited and unnecessary calls by emergency physicians regarding the status of the patients' examinations are eliminated [63]. Communications are also improved because the use of IT solutions allows for a safer and more efficient distribution information that was previously scattered across multiple people and different records [22, 60]. Furthermore, discussions regarding discharge planning transformed from being unstructured to a structured process, resulting in increased transparency [22].

On the other hand, electronic dashboards can have a negative effect on communications because physicians might assume that a data entry replaces their previous way of communicating, resulting in decreased direct interaction and an overreliance on computer systems [65]. Manual whiteboards were sources of interactions because they were often placed centrally in the ED and users gathered here when they were adding data or searching information [41]. Staff members would regularly scan the board and use this as an opportunity to review patients' status of coworkers. This decreased partially with the introduction of electronic dashboards, which resulted in moving work away from a collaborative effort to a more individual effort [41, 66]. Before the introduction of electronic dashboards, brief communications were observed around the dry-erase whiteboards, where less experienced physicians received extra information and recommendations from more experienced physicians. These brief communications informally ensured the quality of treatment. Because of the loss of this form of communication, patient care can potentially worsen [53].

Unintended consequences Some studies also report unintended negative consequences resulting from the introduction of electronic dashboards. Electronic dashboards are inflexible to shorthand notations, the use of symbols and the placement of text in margins [17, 44]. That is because the dashboards require no, or limited input. When dry-erase whiteboards were used, the users could enhance the whiteboards with notes and remarks. The electronic dashboards that replaced these whiteboards only visualise information, limiting the possibility to add personal notes. This shortcoming can have an impact on the workflow of the providers because they often use their own personal recognisable notations to indicate future tasks. Likewise, Pennathur *et al.* [66] and France *et al.* [60] also found that the inability to use personal notations and remarks could negatively impact working practices.

Furthermore, Lee *et al.* [20] found that the availability of a lot of information can cause information overload and scattering. As a result a physician risks losing a lot of time collecting basic data and miss crucial information leading to medical errors.

3.3 Shortcomings of current dashboards

A review by Rasmussen [17] revealed that most of the ED-specific systems reviewed, presented data in a tabular format which is not the most effective form of information visualisation. By solely presenting tabular data, they do not provide aggregate information to visualise the flow of patients or predict imminent crowding [67]. Tabular displays provide limited possibilities for interaction leading to sub-optimal use of data [24]. Although the replacement of dry-erase whiteboards by electronic dashboards certainly led to process improvements in terms of efficiency and communication of information, it is important to update these new solutions to provide information in the form of more effective visualisations.

Input in electronic dashboards is often standardised, but in a complex environment like an ED not everything can be standardised [65], e.g., "triage requires flexible questioning of patients based on patient profiles or presenting problem, and does not progress in one standard, sequential way" [66]. This imposed structure of electronic dashboards potentially lowers its flexibility. Also regarding language, flexibility is lost. Electronic dashboards often use standardised lexicons that, once codified, become static such that no on-the-fly changes can be made or event driven customisations are (easily) possible. When using manual whiteboards, these type of customisations are of course easily achieved [41].

Lastly, one possible problem with electronic dashboards is the occurrence of so called alert fatigue. An overload of unsystematic alerts can lead to situations where clinicians purposely neglect the dashboard and other alerts leading to a decrease in the effectiveness and potential benefits of the decision support system [68, 69]. There needs to be a balance between signaling and noise [68].

Effect	Studies
Patient throughput	[56]
Patient care and satisfaction	[18], [24], [42], [57], [58], [59], [60], [61], [62], [63], [64]
Integration	[61]
Communication	[22], [41], [43], [53], [60], [63], [65], [66]
Unintended consequences	[17], [20], [44], [60], [66]

Table 3
Effects and consequences of use of dashboards in the ED

3.4 Requirements of ED dashboards

This section discusses the most important requirements cited in the consulted literature. The results are presented in table 4.

Real-time The requirement of providing information in real-time is mentioned in many studies as one of the most important features [18, 24, 33, 41, 43, 69]. Franklin *et al.* [24] suggest that real-time availability is important because non real-time dashboards cannot optimally support fast decision making. Operational statistics should be calculated and displayed (near) real-time to support decision making about ED capacity and patient flow [43].

Clear and concise Furthermore, with a limited amount of visual area available on the screen, the dashboard should display aggregate information and allow the users to drill down to details or select specific time periods [21, 55]. The information should be displayed in a clear and concise way such that users can promptly interpret relevant information [33], there is no information overload, and the required on-the-job training is minimised [18, 20, 21, 43, 69].

Generic Martin *et al.* [33] suggest that the dashboard should be generic, such that it can easily be implemented in other EDs.

Privacy The information visualised should adhere to privacy regulations [18, 33, 41].

Alerts Recent studies also suggest to provide different types of alerts. Patient-level alerts can improve the quality of care and patient safety by alerting doctors when certain tests are completed [70]; when processes are delayed/have been completed [18, 69]; or when a patient needs accelerated clinical interventions as a result of adverse events [52]. These alerts can be enhanced by the use of colours [18, 70]. Hertzum M. [67] also found that clinicians want an early crowding warning based on aggregate dashboard information.

Portability Aronsky *et al.* [43], Mazor *et al.* [19] and Wong *et al.* [22], suggest a portability feature which enables access to users anywhere in the ED or even in the network, such as staff not physically present in the ED, to improve communication and to ensure continuity of care and efficient workflows.

Forgiveness Miller *et al.* [69] suggest the dashboard should also allow for "forgiveness". When the dashboard enables the users to provide input (e.g., manual data entries), it should also provide the flexibility to reverse actions (e.g., wrong entries).

Human-centered design Many recent studies suggest to develop the electronic dashboard using a human-centered design, systematically incorporating end-user feedback throughout the design process [71, 72]. The involvement of end-users mitigates the risk of creating ineffective solutions which do not meet the needs of the users [72], ensures that the dashboard supports the goals of the end-users and fits the organizational context [73], improves the chances of successful adaptation by the care providers, and it also enables the developer to select relevant measures, visualisations and comparisons [21, 74]. Franklin *et al.* [24] found that involving the end-users in the development of the dashboard ensured that users, at all time, were able to maintain situation awareness. The failure to maintain situation awareness may lead to a decrease in the quality of care resulting in an increased risk to patients [75].

Requirements	Studies
Real-time	[18], [24], [33], [41], [43], [69]
Clear and concise	[18], [20], [21], [33], [43], [55], [69]
Generic	[33]
Privacy	[18], [33], [41]
Alerts	[18], [52], [67], [69], [70]
Portability	[19], [22], [43]
Forgiveness	[69]
Human-centered design	[21], [24], [71], [72], [73], [75], [74]

Table 4
Requirements

3.5 Universally accepted crowding metrics

Several standardised crowding measures exist. According to Bernstein and Asplin [76], "An ideal measure of ED crowding is universal, reproducible, and consistently accurate across EDs of different sizes. It consists of data elements that are immediately available from existing sources or continuously monitored by existing information systems". The measure should also be programmable into tracking systems such that it can be used as a real-time crowding measure. Several standardised measures for crowding exist, such as the Emergency Department Work Index (EDWIN) [77, 78, 79], the National Emergency Department Overcrowding Scale (NEDOCS) [79, 80], the demand value of Real-time Emergency Analysis of Demand Indicators (READI) [81], the International Crowding Measure in Emergency Departments (ICMED) [82] and the ED Work Score [78, 81]. Hoot *et al.* [81] found that all these measures performed reasonably well at measuring crowding in real-time, but none of them outperformed the ED occupancy level, the most simple measure of them all.

4 Results

This study follows the principles of design science research (DSR) based on the framework of Johannesson and Perjons [25]. The first step of DSR is the problem explication. For the results of this step, the user is referred to section 3 "Related work". In the remainder of this section, the development of the generic crowding dashboard is explained following the other steps from the DSR framework as outlined in section 2.2.1.

4.1 Artifact and requirement definition

The goal of the dashboard is to provide real-time information on the current status of the ED to enable staff members to proactively judge the situation and take corrective actions accordingly. Before the development of the dashboard, requirements were listed and divided in functional and non-functional requirements. Functional requirements specify functions the dashboard should provide while non-functional requirements address general qualities such as usability [25].

The requirements of the dashboard were selected based on the results of the focus group and the findings of the consulted literature. Four functional requirements were put forward:

– The dashboard should provide information in real-time.
– The dashboard should present both patient-level information and aggregate statistics.
– The dashboard should visualise ED crowding in a non-binary way enabling users to judge the current situation based on their knowledge and experience.

– The dashboard should include standardised measures for crowding.

Regarding the fourth requirement, it should be noted that the main focus of the dashboard is providing information in real-time in a non-binary way. However, the results of the focus group also suggested the inclusion of standardised crowding measures.

Besides functional requirements, three non-functional requirements were put forward:

– The dashboard should be generic such that it can easily be implemented in multiple EDs with minimal changes needed to the original design.
– The dashboard should provide information in a clear and concise way enabling users to promptly interpret relevant information.
– Information should be provided in an unambiguous way, minimising possible misinterpretations.

4.2 Design and development of the artifact

4.2.1 Design

The artifact of this study is an ED dashboard. Several initial concepts of the dashboards were sketched to illustrate the layout of the dashboard based on the results of the focus group. The sketches were then enhanced based on the requirements found in the literature of the existing ED dashboards. The final concept of the dashboard was evaluated by two experts in the field of ED dashboards and emergency departments. This resulted in some final improvements to the concept.

4.2.2 Structure

The structure of the final concept of the dashboard is presented in figure 2. In order to maintain the generic character of the dashboard, eight parameters are added to specify site-specific settings. The first six parameters describe the ED regarding staff and infrastructure. The other two parameters are thresholds for the READI and ED Work Score crowding indicators. The current time parameter is used for the demonstration of the dashboard. All indicators and visualisations reflect the status of the ED at this selected time.

The dashboard itself is divided in ten tabs. The first six tabs fulfil the first three functional requirements providing real-time, non-binary information both at patient-level and for the overall ED. The last four tabs present the universal ED crowding measures and their input parameters thus fulfilling the fourth functional requirement.

The first tab provides an overview of the overall ED. The second tab presents a high-level process model of the ED to enable users to quickly assess in which stages of the care process the patients are situated. The third tab presents six important time intervals by visualising the mean and median, the dispersion measures (e.g., standard deviation, interquartile range) and the minimum and maximum per hour for the last 24 hours. The fourth tab is similar to the second tab but with the physical location, enabling the physicians and nurses to find the exact location of all the patients present in the ED. The fifth tab contains a large table with information of all patients present in the ED (e.g., age, sex, triage code, unit, active waiting times). The sixth tab enables the user to select one patient to assess all information of that patient (e.g., age, sex, laboratory process, medical imaging process, visited locations). The last four tabs contain the selected standardised ED crowding measures, i.e. READI, ICMED, ED Work Score and NEDOCS.

Figure 3 shows a screenshot of the structure of the dashboard. The box in the top left corner, above the tabs, shows the selected time. Note that the four crowding indicators are listed below the "Metrics" tab as well as the input parameters with details specific for each site. Based on the selected tab and provided input, information is visualised in the rest of the screen. For a full overview of the design of the dashboard, the reader is referred to Appendix A.

4.2.3 Input data format

The input data format used by the dashboard is an event log. Each row of the log represents one activity and includes the timestamp of the start of the activity, the activity description, information at patient-level (i.e., ID, age, sex, allocated unit and triage code) and the current location of the patient. Several time intervals are then calculated for each patient at the level of each activity and added to the event log, i.e. the current length of stay, the current boarding time, the current bed allocation time, the current laboratory interval, the current medical imaging interval and the current door-to-doctor time. It should be noted that the locations were manually imputed to show the functionalities of the dashboard. The locations should be added to the data by the hospital information system when extracting the data. It should also be noted that the input file for the dashboard is the result of a series of preprocessing steps.

In the original input file, one row represented one patient. Thus, there is one column for each possible activity, containing the start timestamp. This results in a large number of NA values because when an activity is not registered for a patient, the timestamp is

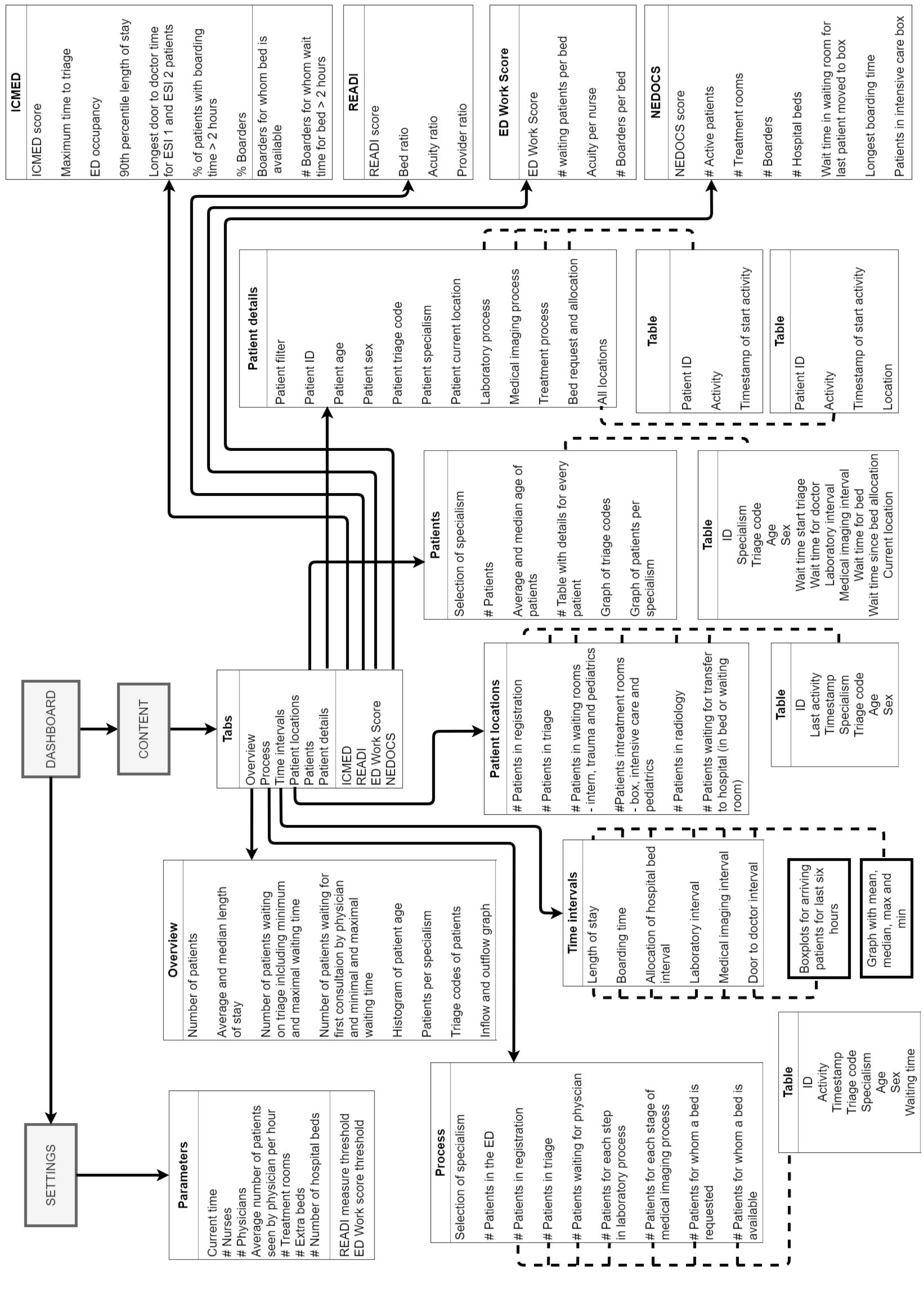

Fig. 2: Diagram of dashboard structure

listed as not available. In this format it is also more difficult to maintain an overview of the current locations of patients, because one column should be added each time a patient is transferred from one location to another. Furthermore, using an event log, changes in the status of a patient (i.e., new activities in the process) can be captured more easily because instead of changing NA values to timestamps or extracting the whole table every time a change is logged, a row is simply added to the existing event log for this new activity. Therefore, this input file was transformed from one row per patient to one row per activity in order to create an event log.

By using a standardised data format, the dashboard can more easily be implemented across multiple EDs. When a standardised input format is used, the dashboard can be used everywhere, as long as the input format is respected.

4.3 Artifact demonstration

To simulate the use of the dashboard in a real-time context, the dashboard is initialised on April 1st, 2011 at 7 pm. The number of nurses and physicians is set at twelve, the number of treatment rooms is set at fourteen, including eight boxes, three resuscitation boxes and three pediatric boxes. The number of extra beds is set at six. The total number of beds on inpatient units, which is needed for the calculation of the NEDOCS score, is set at 2000 beds. Furthermore, the amount of patients seen per doctor per hour, which is needed for the calculation of the provider ratio of the READI score, is initialised at five. Lastly, the threshold for the READI score is set at seven [83] and the threshold for the ED Work Score is set at 4.77 [78].

Given the input parameters selected, there are 56 patients present at the ED at 7 pm. As shown in figure 3, most of them have an ESI triage score of three. Based on the specialism graph, the patients present at the ED are primarily assigned to internal medicine (IAL) followed by traumato (TRH). Thirteen patients have not seen a physician since arriving at the ED, the longest door-to-doctor time being 346 minutes.

The screenshot of the patient locations tab in figure 4 provides a clear indication that the ED is crowded. All fourteen treatment rooms - eight boxes, three resuscitation rooms and three pediatric rooms - are occupied and thirteen patients are waiting in the waiting rooms of the ED. At this moment in time, there clearly is a problem with patient transfers from the ED to the hospital and discharges from the ED. Five out of six extra beds are occupied while another twenty patients are waiting to be transferred to the hospital or to be discharged from the ED. All four universal crowding measures included in this dashboard also confirm this indication of crowding. Regarding ICMED, all six thresholds are transgressed. As for NEDCOS, READI and ED Work Score, all three measures indicate a situation of overcrowding. For more information, the reader is referred to appendix **??**.

The dashboard was demonstrated using a test dataset for Belgian EDs. The test dataset was transformed to an event log as discussed in section 4.2.3.

4.4 Artifact evaluation

The goal of the artifact evaluation is to determine to which extent the requirements are met [25].

4.4.1 Functional requirements

The first functional requirement specifies that the dashboard should provide information in real-time. Because it is a prototype build on historical data, the dashboard is not implemented in real-time. However, a time selection box is used to demonstrate the real-time functionality of the dashboard, as mentioned in section 4.3. Depending on the time selected, all calculations are adjusted to provide indicators and visualisations for the selected time. This implies that the dashboard will be able to provide real-time support once it is implemented in a real-time environment.

The second functional requirement states that the dashboard should provide information both at patient-level and at system level. This is achieved by creating aggregate tabs, detailed tabs and tabs with drill-down functionalities. The first five tabs initially present data at the level of the overall ED to enable the user to quickly assess the overall status of the ED. Moreover, the process tab and location tab (i.e., the second and fourth tab) provide drill-down functionalities to enable the users to get information at patient-level. The patients tab (i.e., fifth tab) also contains a large table with information at patient-level for all patients in the ED. The patient details tab (i.e., sixth tab) enables the user to select one patient to find all captured information on this patient.

The third functional requirement indicates that the degree of crowding should be represented in a non-binary way. The dashboard fulfils this requirement by presenting visualisations and indicators without value judgement. Consequently, the estimation of the degree of crowding in the ED is assigned to the user of the dashboard based on his or her personal interpretation.

The fourth and last functional requirement specifies the requested inclusion of universally accepted standardised measures for crowding to use for comparisons. This is achieved by including four measures,

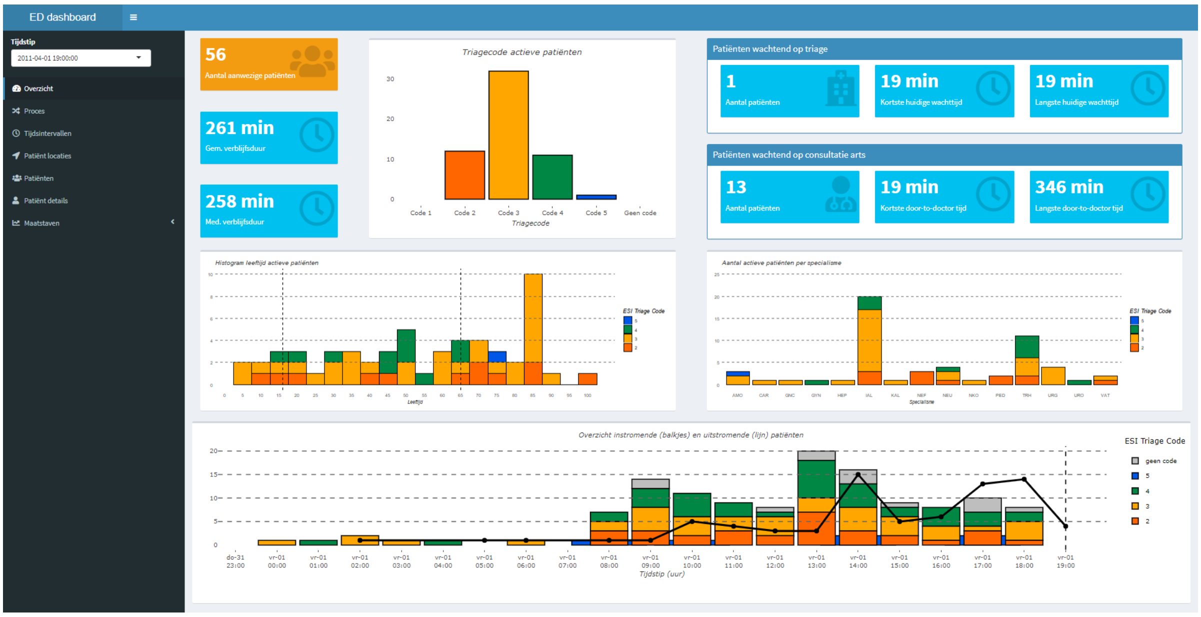

Fig. 3: Screenshot of dashboard structure (overview tab on April, 1^{st}, 2011 (7pm))

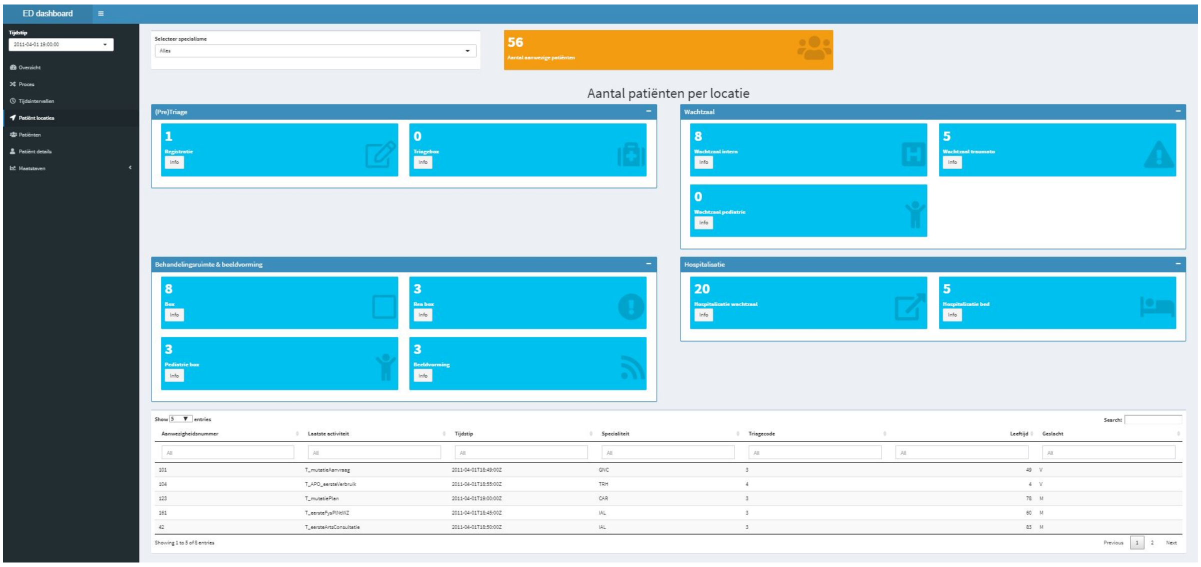

Fig. 4: Patient locations tab on April, 1^{st}, 2011 (7pm)

i.e. ICMED, READI, ED Work Score and NEDOCS. It should be noted that the main focus of the dashboard is providing information in real-time in a non-binary way. Therefore, the four crowding measures are included as sub tabs underneath the metrics tab (figure A.5), such that the focus remains on the other tabs of the dashboard.

4.4.2 Non-functional requirements

The first non-functional requirement stipulates that the dashboard should be generic such that it can easily be implemented at other EDs. In contrast with most other existing dashboards, this dashboard is not created for the use at one specific ED. The dashboard was developed based on the findings of a focus group of representatives of five EDs and on the consulted literature. This ensures that the indicators included in the dashboard are relevant for more than one ED. Furthermore, for the specific details of the emergency departments, which are only used for the calculation of the standardised crowding measures, a limited number of input parameters are used. Based on these parameter settings, the crowding measures are adjusted. When the right information is provided, the dashboard can easily be replicated at different sites. These parameters can easily be hard-coded in the source code of the dashboard by the IT departments of the EDs such that they do not need to be initialised whenever the dashboard is used. The use of a standardised input format in the form of an event log also makes it easier to implement the dashboard in other EDs. Every ED should be able to use the dashboard as long as the right information is provided in the right format.

The second non-functional requirement states that information should be provided in a clear and concise way. In order to do this, the dashboard is split up in multiple tabs. Moreover, the input of the potential end-users was requested in order to only select relevant indicators and visualisations. The overview tab also summarises the most important indicators to enable users to promptly capture the current situation of the ED.

The final non-functional requirement states that information should be provided in an unambiguous way. This is done by only providing indicators and visualisations without any value judgement (except for the standardised crowding measures). This way, the decision responsibility is assigned to the user based on his or her personal interpretation, limiting the possibility of misinterpretations.

Based on the evaluation discussed in this section, it can be concluded that the dashboard meets the aforementioned requirements. However, enforcement of this evaluation could be accomplished by implementing the dashboard in practice and letting the users evaluate the dashboard.

5 Discussion

The dashboard developed in this study could provide the nurses and physicians in the EDs with a powerful and user-friendly tool to assess the state of patients present in the ED as well as the overall state of the ED in real-time. Although several dashboards for intended use in EDs were already developed in other studies, this study tries to alleviate some of the limitations of these dashboards. More specifically, two limitations were tackled.

Firstly, most of the existing dashboards are developed for the use in one specific ED, limiting the usability of the findings. Therefore, an important requirement for this study stipulated that the dashboard should be generic, such that it could be easily implemented across different EDs. By using the input of a focus group consisting of representatives of five EDs, it is ensured that the selected indicators are relevant to more than one ED. Furthermore, by creating a standardised data input format in the form of an event log, the dashboard can be easily implemented as long as the data is provided according to the input format (section 4.2.3). Moreover, no site-specific details are needed for the first six tabs of the dashboard. Furthermore, the need for hospital specific details that should be included is limited. The details that are needed to calculate the standardised crowding measures (e.g., number of inpatient beds, number of patients seen per doctor per hour) are included as parameters. This way, the use of the dashboard is not limited to one specific ED, but the dashboard can be fitted to multiple EDs by changing these parameters. They can be changed when using the dashboard or can be hard-coded in the source code by the IT department of the ED, such that they do not need to be initialised whenever the dashboard is used.

Secondly, several existing dashboards only provide data at patient-level or at system level, which limits situation awareness [24]. The dashboard developed in this study improves situation awareness by providing both aggregate statistics as well as information about individual patients. The overview page of the dashboard, shown in figure 3, only provides aggregate statistics enabling the users to gain an understanding of the status of the overall ED at a glance. The other tabs of the dashboard provide aggregate information by default, but they also provide the possibility to drill down to more detailed information. This way, the user can easily get an overall understanding of the ED and drill down to follow the cases of specific patients when needed.

This dashboard also is an improvement on the existing dashboards because it presents information about the physical location of the patients and the stage of care process where the patients are situated. The inclusion of information about the physical location of each patient enables the user to quickly detect crowded areas in the ED. By using the drill-down functionalities, the nurses and physicians can then assess which patients are situated in these areas and take actions accordingly. It also enables the users to quickly locate specific patients in the ED. Besides the physical locations of the patients, the dashboard also visualises each patient's stage in the care process. Using this information, the care providers can assess in which stages of the process problems or bottlenecks arise and formulate plans to alleviate the them.

The dashboard was developed with the intended goal of providing a decision support tool that provides information in a non-binary way. This enables users to take proactive measures based on their judgement, using the dashboard as a support tool. Therefore, the dashboard developed in this study serves as a management tool, providing real-time information about the patients currently present in the ED. Apart from the standardised crowding measures, the dashboard only provides indicators and visualisations without value judgement. This way, the interpretation responsibility is assigned to the user, limiting bias and the risk for misinterpretations.

Besides real-time information, the dashboard also provides insights based on longitudinal data. The dashboard contains information about the inflow and outflow of patients over time as well as longitudinal data of important time intervals (e.g., length of stay, boarding time, laboratory interval, medical imaging interval, door-to-doctor time and time between bed request and bed allocation). Because the dashboard also presents these insights, it can also be used to detect inefficiencies, implement process improvements and evaluate the effects of these improvements. The effects can be evaluated by analysing the evolution of the longitudinal data, i.e. by comparing the data before and after the process changes.

6 Conclusion

The dashboard developed in this study provides the EDs with a tool to proactively manage the ED. It presents aggregate information on the status of the ED and it also provides drill-down functionalities to enable the users to follow the cases of specific patients. Furthermore, it also provides information on the physical location of the patients and the stage in the care process where each patient is situated. This enables the users to easily detect bottlenecks and to find the patients who cause these bottlenecks or are affected by them.

This study presents the process of creating a generic dashboard for EDs, providing real-time information at patient-level and aggregate statistics for the ED as a whole. The end-users were included in the original design of the dashboard by means of a focus group to determine which relevant indicators should be included in the dashboard. The study follows the methodological framework of design science research of Johannesson and Perjons [25] to provide a clear description of all the steps in the design process.

Three contributions are made by this study. Firstly, the most promising feature of the dashboard is its generic character. The dashboard was developed based on the findings of a focus group of representatives of five EDs and on the consulted literature. This ensures that the dashboard is applicable to more than one ED. Furthermore, the use of event log data provides an easy data input format for this purpose. Moreover, by using parameters the dashboard can easily be fitted to every interested specific ED. Secondly, the dashboard provides real-time information at patient-level and aggregate level as well as universally accepted crowding measures. And lastly, the dashboard also provides information about patients' physical locations in the ED as well as in which stages of the care process they are situated.

Several interesting challenges for future work can be formulated. Firstly, during the focus group used in this study only representatives of five EDs were consulted. Consulting more EDs over a larger area could provide more insights regarding the design that could improve the usability of the dashboard. Secondly, the usability of the dashboard could be tested by studying its use on the working floor. This would also indicate the dashboard's real contribution to the EDs. Lastly, because of the COVID-19 crisis in 2020, the intended evaluation of the dashboard by the end-users could not be performed. Therefore, a screencast of the demonstration of the dashboard is sent to the representatives of the EDs, in order to show them the final result. Future work could integrate the feedback provided by the representatives to improve the current dashboard.

Future work could also improve the current dashboard by including colour coded alerts, especially on the process and locations tab. Colours could indicate at which stages or locations too much patients are situated increasing the risk for bottlenecks, i.e. orange could be used to warn the user that a certain threshold for the amount of patients in a stage/location is almost exceeded, while red could indicate that the threshold is transgressed. Secondly, the dashboard could by enhanced by including patient safety indicators. Lastly, machine learning could be used to predict when crowding could occur or predict the process of individual patients.

Appendix A Generic ED dashboard

In the appendix, the content of the tabs of the dashboard is presented. There are six main tabs displaying indicators and visualisations without value judgement and there are four sub tabs, one for each of the standardised crowding indicators (i.e., ICMED, READI, ED Work Score and NEDOCS).

A.1 Overview tab

The overview tab, which is presented in figure 3 (section 4.3), contains four graphs and eight measures. The first graph, in the top row of the screen shows the number of patients present at the ED for each triage code. The two graphs in the middle of the screen present the patient population by age and the units to which the patients are assigned. The colours reflect the composition of each group in terms of the triage code. The graph in the bottom of the screen presents the evolution of the inflow (bars) and outflow (line) of the patients for the last 24 hours in intervals of one hour.

The first measure, the yellow information box, indicates the number of patients currently present at the ED. The two measures underneath show the mean and median length of stay for the active patients. The other six measures are divided in two groups. The first group presents the number of patients waiting for the start of triage and the associated minimum and maximum waiting time. The other group presents the door-to-doctor time for all patients not yet consulted by a doctor as well as the minimum and maximum waiting time. These two groups do not include patients heading to a resuscitation box because for them the process is different, which would lead to distorted values when included.

A.2 Process tab

The process tab, shown in figure A.1, shows in which steps of the care process the patients present in the ED are situated. The process is divided in four parts, (pre)triage, doctor, treatment & medical imaging and hospitalisation. The process in the ED is very complex and is different for every patient [12]. Therefore the process presented in this tab serves as a high-level structure of the process. The (pre)triage step displays the number of patients waiting for the start of the triage and the patients in triage. The next information box contains the number of patients who have not yet been seen by a doctor, thus also including the patients in the previous information box. The third information box presents for which patients the laboratory and medical imaging processes are active or finished. For both processes, it presents the number of patients waiting for the process to start, the patients currently in the process and the number of patients for whom the last report is available. The last information box presents the number of patients waiting for a transfer to the hospital. This information box is divided in the number of patients waiting for a bed to become available and the number of patients for whom

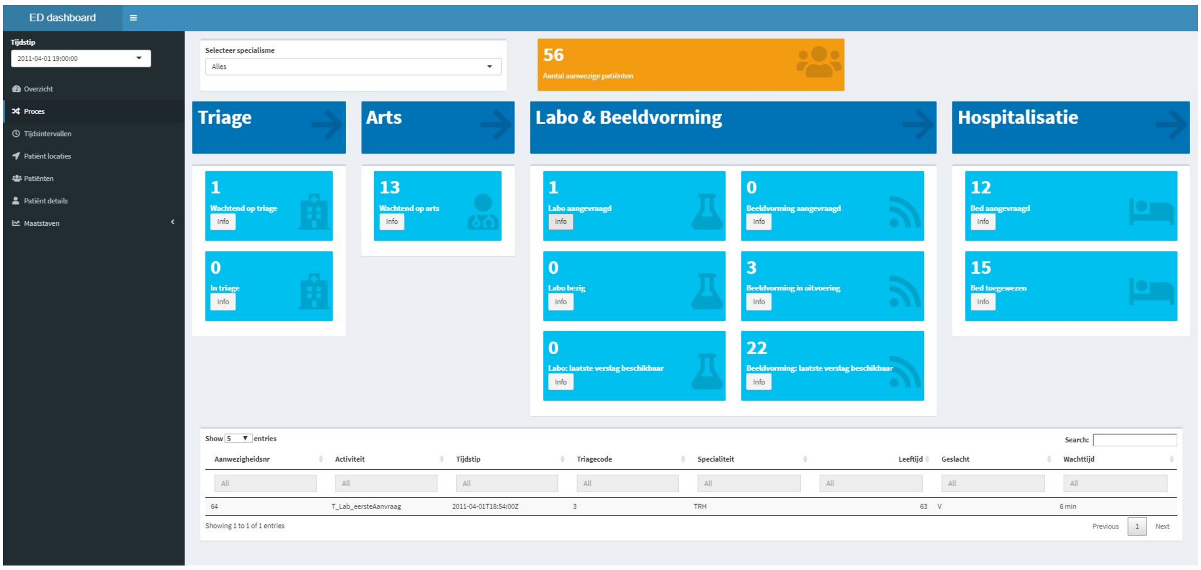

Fig. A.1: Process tab on April, 1st, 2011 (7pm) a bed is available but are still present in the ED. Patients can thus be situated in multiple stages of the process simultaneously (e.g., the laboratory sample of a patient can be analysed when the patient himself is in the radiology stage). The goal of this tab is to provide the user with information about in which stages in the process problems arise. Here, the user can see where bottlenecks are starting to arise or have already been formed.

Each information box also contains a button that enables the users to drill down to the level of individual patients. This way, the user can access detailed information on which patients are situated in the selected stage. This can help the user in finding the patients contributing to certain problems or patients who are affected by the problems. The user can also filter on a single unit to get an overview of the patients in each stage of the process for the selected unit.

Future work could improve this tab by using colour schemes to alert the user when problems are starting to form or have been formed. This can be done by implementing thresholds that indicate when too much patients are in a certain stage (e.g., orange when the threshold is almost reached and red when it is transgressed).

A.3 Time intervals tab

The time intervals tab, presented in figure A.2, contains six time intervals based on the results of the focus group and the findings of Martin *et al.* [33]. These are the length of stay, boarding time, time until allocation of hospital bed, laboratory interval, medical imaging interval and door-to-doctor time. The intervals are calculated for all currently present patients. Each time interval only includes data for the patients for whom the time interval as currently active (e.g., door-to-doctor time is only calculated for patients waiting for a doctor). As these intervals tend to have a positive skew, the mean and the median are included in the tab. The median is much less influenced by outliers than the mean is. Again, a filter is included to enable the users to get an overview of the time intervals for a specific unit.

Underneath these indicators, a graph depicts the evolution of the mean an median values for all intervals for the last 24 hours. It is possible to select or deselect certain lines, or to zoom in on certain time intervals.

Moreover, it is also possible to get a detailed view of one of the time intervals by clicking on the action button underneath the values. This presents a graph for the last 24 hours, containing the mean, median, minimum, maximum, interquartile range and standard deviation per hourly interval.

A.4 Patient locations tab

The patient locations tab is very similar to the process tab. As shown in figure 4 (section 4.3), the ED is divided in four main areas, i.e. (pre)triage, waiting

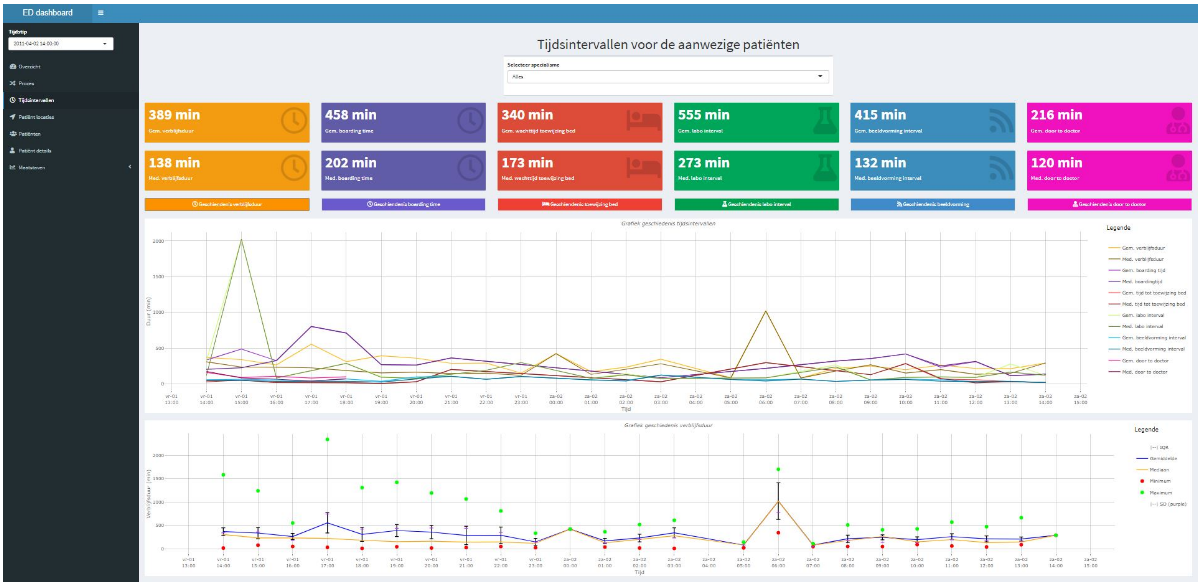

Fig. A.2: Time intervals tab on April, 2^{nd}, 2011 (2pm) rooms, treatment rooms & medical imaging and hospitalisation. The values in each information box indicate the number of patients physically present at this location. A patient can only be present at one location. The goal of this tab is to visualise the crowded areas in the ED and the physical location of all the patients present in the ED. A drill-down functionality is added to each information box to enable the user to request a table with details about the patients present at the selected location. At the top of the tab, an information box is added to display the total number of patients present in the ED. By adding a filter, the user can also select a unit to get an overview of the locations of the patients allocated to this unit.

It should be noted that the data about the locations was not initially included in the dataset. Therefore the data about the locations is manually imputed to the dataset to show the functionalities of the dashboard. However, it is possible to track the physical location of the patients using tracking devices or by updating the location in the information system each time a patient moves to another location.

The patient locations tab can also be enhanced as described for the process tab. Colour schemes could be used to alert the user when areas start to get crowded or are already crowded. This can be done by implementing thresholds that indicate when too much patients are simultaneously present at one location (e.g., orange when the threshold is almost reached and red when it is transgressed). This could help the user to quickly assess the situation in the ED and act accordingly.

A.5 Patients

Figure A.3 shows a screenshot of the patients tab. Six information boxes are displayed at the top of the page, presenting the mean and standard deviation [1] of the time intervals included in the table underneath, i.e. wait time for start of triage, door-to-doctor time, laboratory interval, medical imaging interval, wait time for bed and minutes since allocation of a bed. The table underneath contains personal details about all the patients present in the ED, i.e. presence number, unit, triage code, age and sex, as well as current waiting times of the patients. The table only contains the waiting times currently active for the patients. Moreover, the user can filter on specific units to see details about all the patients currently allocated to that unit.

Underneath the table are two graphs presenting information at the overall level of the ED. Both graphs can also be found on the overview tab. The graph on the left shows the number of patients per triage code and the graph on the right displays the number of patients per unit. The colours in the second graph represent the number of patients per triage code.

Again, future work could enhance this page by including colours. The colour of the information boxes on the top of the page could be triggered by certain thresholds (i.e., the box for the mean door-to-doctor time could turn red when it exceeds 25 minutes).

[1] The standard deviation is calculated using n-1 in the denominator. When data is calculated for one patient only, the standard deviation equals "NA".

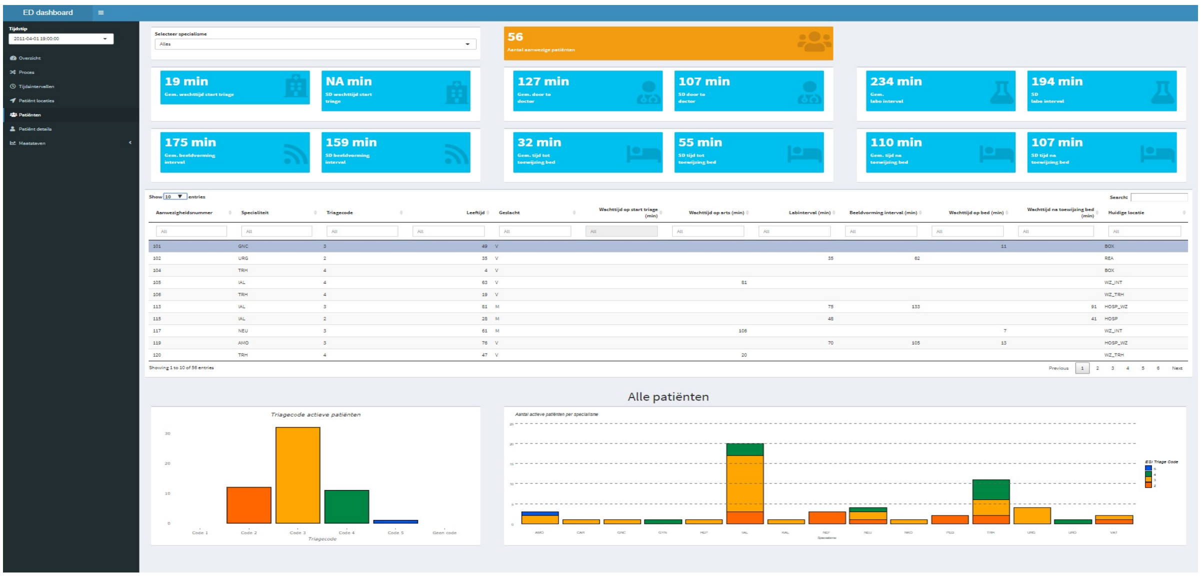

Fig. A.3: Patients tab on April, 1st, 2011 (7pm)

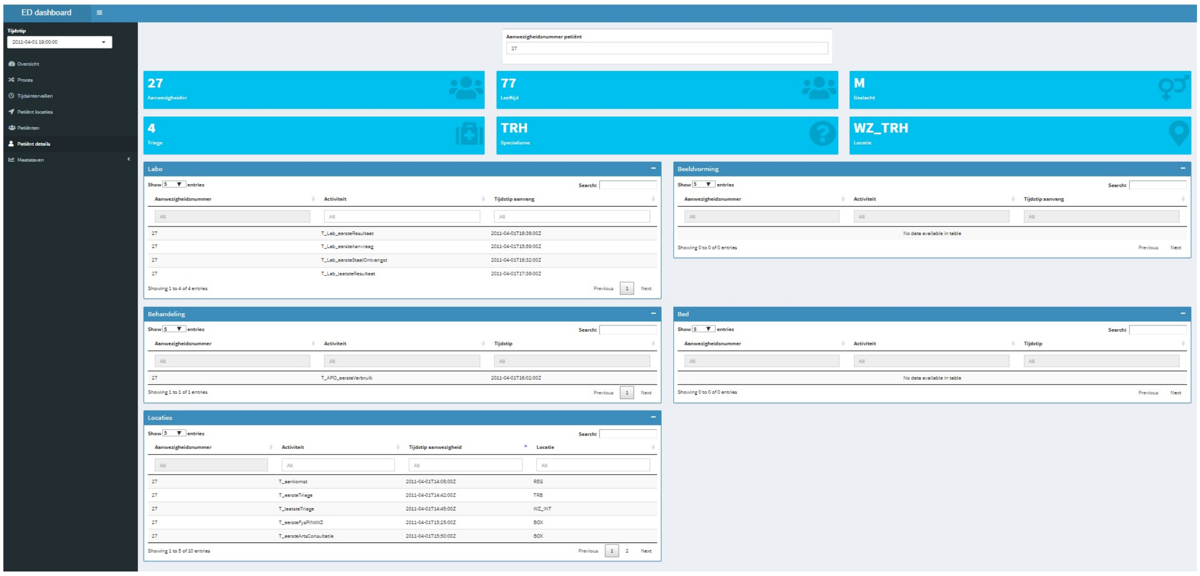

Fig. A.4: Patient details tab on April, 1st, 2011 (7pm) for patient 27

A.6 Patient details tab

The patient details tab, shown in figure A.4, enables the users to select one patient. On this page, nurses and physicians can get a detailed overview of a patient's details and current state, i.e. age, sex, triage code, unit and current location. The user can also consult historical data about the specific process stages the selected patient has underwent and locations he or she has visited during his or her stay. The first four tables represent processes and provide the presence number of the patient, the activity name, and the start time of the activity. Four processes are included in this tab, i.e. laboratory, medical imaging, treatment [2] and hospitalisation (i.e., bed request and bed allocation). The last table presents the locations the patient has visited during his or her stay in the ED. This table shows the first activity at a certain location as well as the start time of this activity.

A.7 Metrics

The dashboard also includes four standardised crowding measures, i.e. ICMED, READI, ED Work Score and NEDOCS. The goal of this study is the creation of a generic ED dashboard providing non-binary indicators. Because the crowding measures do not fully adhere to this goal (i.e., they indicate whether the ED is crowded or not), they are included as sub tabs under "Metrics". Thus, the user can consult them when needed, but the focus is placed on the other tabs of the dashboard. When the metrics tab is selected, a list of parameters appears, as presented in the bottom left corner of figure A.5. The parameters are needed for the calculation of the crowding measures and are the only hospital-specific details required in this dashboard.

The parameters can be changed whenever the dashboard is used, or can be hard-coded by the IT department of the EDs using the dashboard such that they do not need to be initialised whenever the dashboard is used.

A.7.1 ICMED tab

In contrast to the other crowding measures included in the dashboard, the ICMED is not a calculated value, rather it presents a number of threshold transgressions (figure A.5). Boyle *et al.* [84] suggest eight measures accompanied by thresholds. Three transgressions or more are used as a predictor of crowding. The dashboard developed in this study uses six of the eight measures proposed by Boyle *et al.* [84]. The two measures not included in the dashboard are the ability for ambulances to offload patients and the number of patients who left without being seen. The first measure is omitted because there was no data available in the dataset to calculate it. The second measure was excluded because it is not possible to calculate the number of patients who left without being seen in real-time as you can not gauge whether a patient will or will not be

[2] Indicated by the first time something was taken from the electronic medicine cabinet.

consulted by a physician in the future.

Colours are used to present a violation of a threshold and to present the state of the ED. Underneath the individual indicators an information box is added to provide information on the calculation and the meaning of the ICMED score (e.g., see figure A.6). Two additional measures are included in the ICMED tab, i.e. the number of boarders [3] for which a hospital bed is available and the number of boarders that are currently waiting for a bed for over two hours. These values have a more intuitive meaning as they are not presented as percentages.

[3] Patients that are already admitted to the hospital, for who no inpatient beds were available [76].

A.7.2 READI tab

The READI score is calculated using three crowding indicators, i.e. the bed ratio, the acuity ratio and the provider ratio [81]. As shown in figure A.6, the tab consists of a colour-coded value for the score, with red indicating that the ED is overcrowded and green indicating the opposite. Underneath the score, the values for the three building blocks of the READI score are presented. Lastly, the formula and the meaning of the building blocks are explained using an expendable information box.

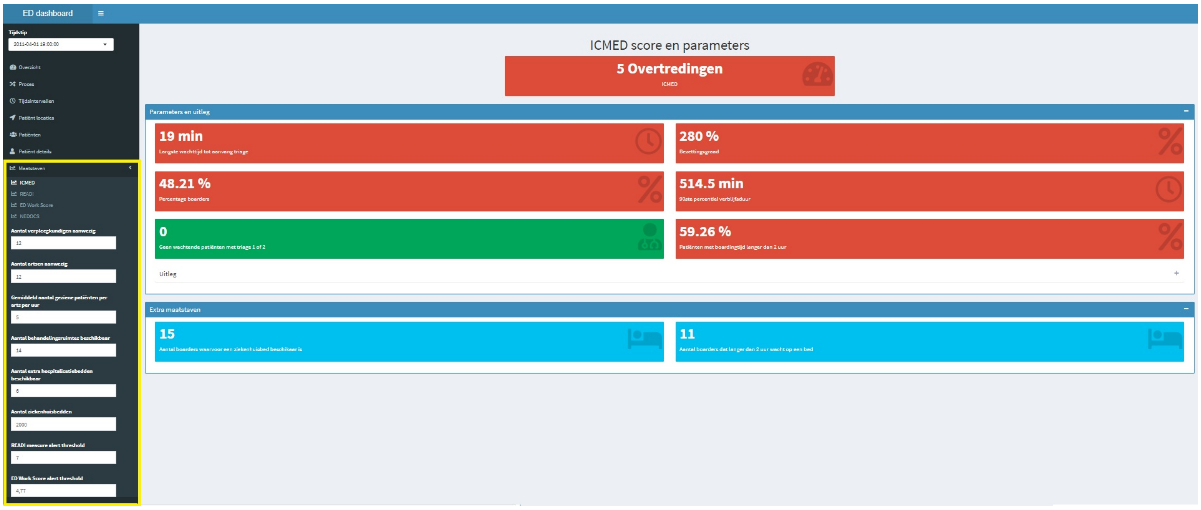

Fig. A.5: ICMED tab on April, 1st, 2011 (7pm)

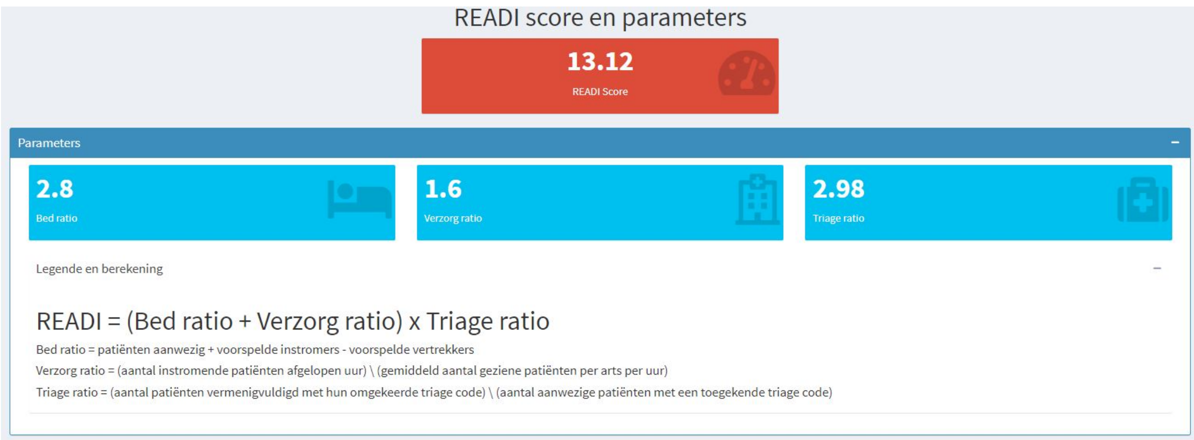

Fig. A.6: READI tab on April, 1st, 2011 (7pm)

A.7.3 ED Work Score tab

The tab of the ED Work Score, shown in figure A.7, has the same structure as the two previously described tabs. Again, the overall value of the measure is displayed in the top of the screen using red or green to indicate whether the ED is crowded or not. The information box underneath contains the indicators used to calculate the ED Work Score, i.e. inflow, throughput and outflow factors, as well as a description and formula for the calculation.

A.7.4 NEDOCS tab

The last tab of the dashboard is the NEDOCS tab, presented in figure A.8. The structure is similar to the other tabs. The information box at the top of the page displays the calculated NEDOCS score based on the individual indicators underneath. The information box is red or green depending on the value of the NEDOCS score. The threshold for the ED to be overcrowded is set at 120 based on the findings of Weiss *et al.* [80]. Similar to the other tabs, the user can find extra information about the calculation of the measure in the expendable information box underneath the individual indicators.

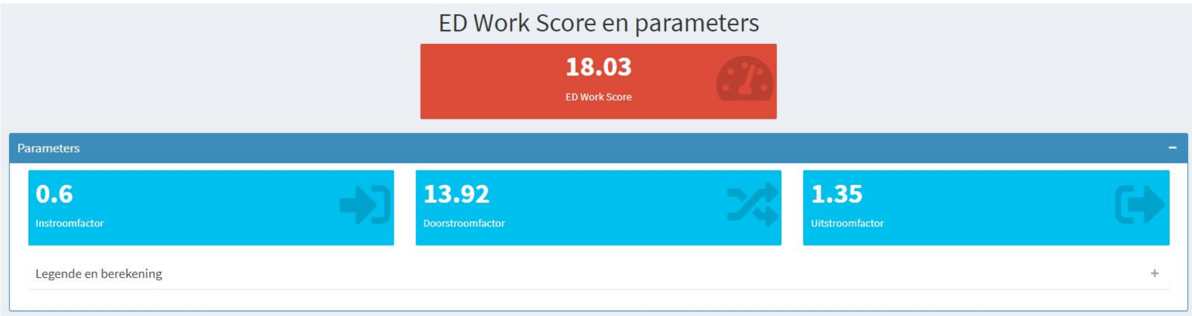

Fig. A.7: ED Work Score tab on April, 1st, 2011 (7pm)

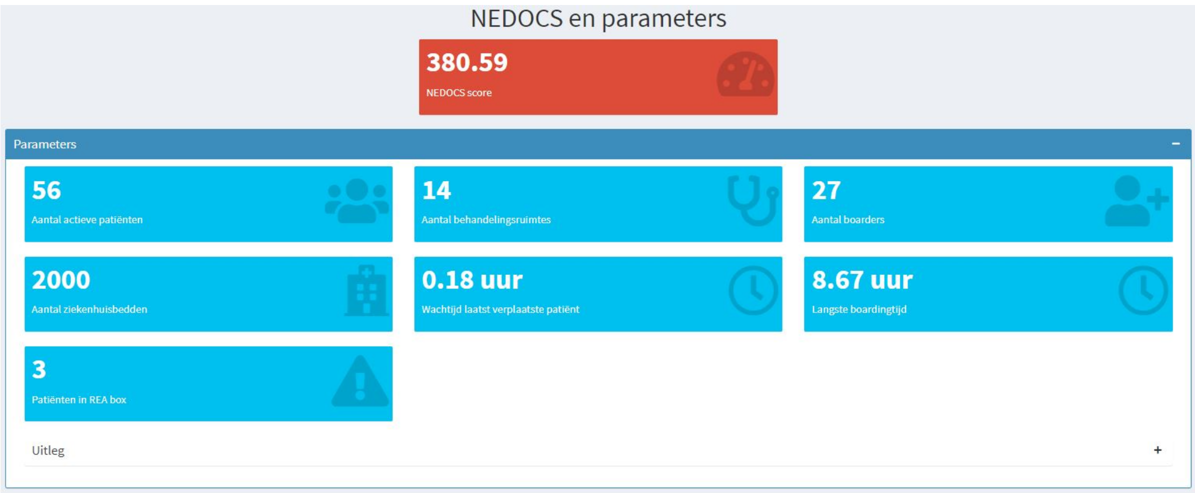

Fig. A.8: NEDOCS tab on April, 1st, 2011 (7pm)

Study	Dashboard content	Strengths	Weaknesses
Martin et al. [33]	- Real-time information - Aggregate overview of status ED - Aggregate time intervals - Throughput statistics - Quality and safety indicators - Crowding measures	- Real-time - Involvement of end- users during design to ensure selection of relevant measures and indicators - Generic and standardised - Visualizations of trends	- No alerting - No drill-down availability to patient-level information
Franklin et al. [24]	- Real-time information - Throughput dashboard visualizing the number of patients in each stage of the process - Summarised statistics for overall ED - NEDOCS value - Colour coded alerts based on thresholds - Filtering availability	- Real-time - Colour coded alerting to improve the perception of the state of a unit in the process - Easy recognition of bottlenecks - Both summarised statistics and patient-level information - Filters	- Build for one specific ED - No clear distinction between aggregate and detailed information
Yoo et al. [18]	- Real-time information - Geographical presentation of ED to visualise specific locations of patients - Aggregate and patient-level information - Patient-level alerts through colour coding and symbols	- Real-time - Patient-level alerts - Both summarised statistics and patient-level information - Overview of where patients are located	- Single-center case - The measures used are not universally agreed upon
Mazor et al. [19]	- Real-time information - Colour coded alerts - Aggregate and patient-level information - Occupancy statistics - Trends in occupancy level	- Real-time - Patient-level alerts - Visualisation of trends - Both summarised statistics and patient-level information - Available at all workstations	- Single site implementation - No information on patient-flow
Lee et al. [20]	- Real-time information - Room map - Current ward operation status - Crowding index - Patient's vital signs - Medical record review screens with detailed information including laboratory and radiology test results - Alerts at patient-level	- Real-time information - Integration with medical records to enable users to consult test results - Patient-level alerts - Both summarised statistics and patient-level information	- Single site implementation

Table A1: Existing dashboards

Study	Dashboard content	Strengths	Weaknesses
Badgeley et al. [52]	- Real-time information - Patient's vital signs over time (personal logs for use by patients) - Visualization of patient locations - Aggregate statistics per unit for patient safety	- Open source - Both summarised statistics and patient-level information - Both real-time and historical data	- No users involved in the design process - Variable names are hard to understand
Aronsky et al. [43]	- Real-time information - One row for each patient containing room; bed; arrival; length of stay; nurse, complaint;test result indicator; and so on - Summary statistics of overall ED status - Colour coded alerts	- Real-time - Both summarised statistics and patient-level information - Detailed patient information on both status and location - Colour coded alerting - Accessible from everywhere in the ED	- Site-specific implementation - Tabular display
Wong et al. [22]	- Real-time information - One row for each room containing detailed information of the patient in the room (or vacancy indicator) and name of attending nurse and physician - Colour coded alerts - Integration with patient's Allied Health care plan	- Real-time - Colour coded alerts - Detailed patient information on both status and location - Accessible everywhere within the network - Integration with Allied Health care plan	- Tabular display - No aggregated statistics - Site-specific implementation
Hertzum and Simonsen [53]	- Real-time information - One row for each room containing detailed information of the patient in the room and name of attending nurse or physician	- Real-time - Detailed patient information on both status and location - Accessible everywhere within the network	- Tabular display - No aggregate statistics - Site-specific implementation

Table A1 (Continued): Existing dashboards

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