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Emergency Department Crowding. Objective Modelling based on Workload

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Objective Modelling based on Workload

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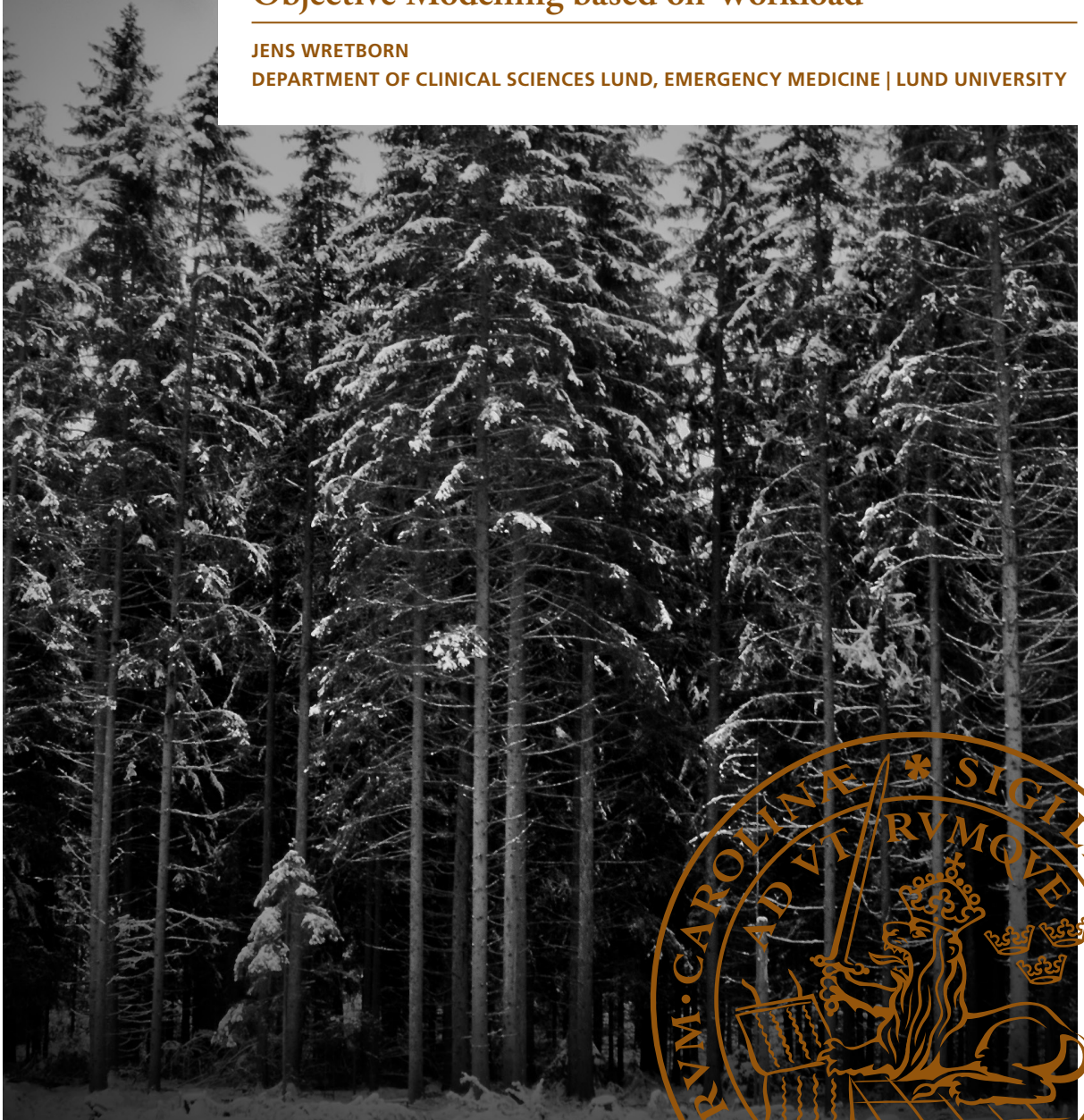
Emergency Department Crowding

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Objective Modelling based on Workload

Jens Wretborn

DOCTORAL DISSERTATION

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Abstract

Emergency Departments (ED) have a central role in modern healthcare, providing emergent care regardless of complaint 24/7. However, EDs are often characterized by long waiting times for patients and a stressful working environment for staff. These are features or a resource and demand mismatch, internationally known as ED crowding. Although several reports and news articles have indicated that ED crowding is a problem in Sweden, there is no systematic work to assess it, nor a validated method to measure it. These things are essential to understand both the severity and extent of the problem, and to evaluate initiatives to alleviate crowding. With this thesis, I aim to begin this process by looking at different aspects of crowding assessment.

The thesis is built upon four studies, each providing a different perspective on how to measure ED crowding. In the first paper we derived a model that can measure crowding, defined by ED staff, based on data from the digital information system in the ED. The model was derived in 5 EDs in the county of Skåne in Sweden and validated in 2 of these EDs. We propose a model that includes the number of patients in the ED, their waiting times and acuity, and that shows promising ability to measure crowding both in the derivation and validation; The Skåne Emergency Department Assessment of Patient Load (SEAL) model. Paper II investigates the prevalence of crowding and boarding, ie when patients are waiting for an inhospital bed in the ED, on a national level in Sweden. The results suggest that crowding is prevalent on a national level in Sweden, with 37% of the survey EDs reporting high occupancy rate during the 24 hour study period. Based on the data collected in paper II, the third paper in the thesis explores the relation between crowding, assessed by staff, and the ratio of patients to treatment beds, also known as the Occupancy Rate. The analysis in paper III indicates that high occupancy rates may not predict crowding as assessed by staff equally between EDs, and that crowding may be influenced by the organisation of the ED. This highlights the importance of systematic measurements of crowding adjusted for ED-specific features, like number of treatment beds. The last paper in the thesis examines the association between crowding and mortality. The results indicate an association between high levels of crowding, measured by a modified SEAL model, and an increased 7-day mortality, confirming that ED crowding is a real threat to the safety of our patients.

This thesis indicates that ED crowding is prevalent on a national level in Sweden and associated with increased mortality for our patients. We would therefore strongly encourage a systematic assessment of crowding as an essential part of the regular quality insurance work, both locally and on a national level. Given the complexity of both crowding and the care in the ED, the assessment should likely include multiple different measures. We suggest using the modified SEAL model since it is a validated measure of crowding with good predictive value and an ability to identify situations where crowding is associated with increased mortality. Further studies should focus on predicting imminent crowding and on methods to reduce its impact on patients and staff.

Key words
Emergency Department, Crowding, Overcrowding

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Emergency Department Crowding

Objective Modelling based on Workload

Jens Wretborn

When a measure becomes a target, it ceases to be a good measure

- Marilyn Strathern

Contents

Preface

Around 2 million patients visit Emergency Departments (EDs) in Sweden every year and most citizens have some relation to emergent care, either as a patient or as a relative. In this thesis I explore how to measure the phenomenon of ED demand and resource mismatch, also known as crowding, from a Swedish perspective.

I will start with a brief background of the Swedish ED system in general and continue with an in-depth introduction to the field of ED crowding, its effects and potential causes. Specifically, this research addresses the issue of how to measure crowding, which I will explain further in the introduction. This thesis encompasses four separate papers that address three different issues around measuring crowding in a Swedish setting.

The first paper investigated whether we could model crowding based on the staffs' perception of workload in a valid and reproducible way. The second paper aimed to address if crowding is a problem on a national level in Sweden. Finally, paper III and IV investigated specific aspects of measuring crowding in the ED. The methods and results of all included papers are presented in sequence in the methods- and result sections. Finally, the discussion and conclusion sections aim to highlight and synthesize the findings of this thesis and some important aspects and potential consequences of the results.

This thesis is not only a synthesis of the included studies but a journey through the development of my knowledge and proficiency as a researcher. Research on ED crowding was largely uncharted territory in Sweden at the inception of this work. Much of my initial knowledge relied on the prominent researchers in the field who produced the influential papers on crowding during the beginning of the twenty-first century, which have provided valuable knowledge and inspiration. However, this thesis has not evolved in a vacuum and for the past decade several important research projects on ED crowding have been carried out in Sweden and internationally, which have provided inspiration and improved many aspects of this thesis. Any failure to reference or give credit where it is due is unintentional.

In the first draft of this thesis, there was a fifth paper. This paper was a natural sequel to our first paper. Due to questions regarding the ethics approval of the data collection at one of the study sites, we decided to exclude the paper from the thesis. An erratum pertaining to these issues has since been published to the journal. Although this issue led to an important dimension of the thesis being lost, which was very unfortunate, the overall results and conclusions remain unaltered.

List of original papers

I) Jens Wretborn, Ardavan Khoshnood, Mattias Wieloch & Ulf Ekelund. Skåne Emergency Department Assessment of Patient Load (SEAL) - A Model to Estimate Crowding Based on Workload in Swedish Emergency Departments. *PLOS One*; June 17, 2015.

II) Jens Wretborn, Joakim Henricson, Ulf Ekelund, Daniel B Wilhelms. Prevalence of Crowding, Boarding and Staffing Levels in Swedish Emergency Departments - a National Cross-Sectional Study. *BMC Emerg Med*. 2020; 20: 50.

III) Jens Wretborn, Ulf Ekelund & Daniel Wilhelms. Differentiating properties of Occupancy Rate and Workload to estimate Crowding; a Swedish national cross-sectional study. 2021. *Manuscript*.

IV) Jens Wretborn, Daniel Wilhelms & Ulf Ekelund. Association between Emergency Department Crowding and ED mortality: An observational multicenter study in Sweden. 2021. *Manuscript*.

Abbreviations

ACEM - Australasian College of Emergency Medicine

ACEP - American College of Emergency Physicians

AuROC - Area under the Receiver Operating Curve

ECS - Emergency Care System

ED - Emergency Department

EDWIN - Emergency Department Work Index

EMS - Emergency Medical Services

HR - Hazard Ratio

LWBS - Left without being seen

NEDOCS - National Emergency Department Overcrowding Score

OR - Occupancy Rate

RCEM - Royal College of Emergency Medicine

ICMED - International Crowding Measure for Emergency Departments

US - United States

Introduction

Emergency Care in Sweden

Although the need for emergent care due to illness or accidents arose with mankind, its history is primarily defined by the societal construct of modern healthcare. The first hospital in Sweden was founded 1752 in Stockholm[1] and the term "olycksfall"(casualty) dates back to 1791 according to the Swedish Academy Dictionary.[2] Similarly, the word "casualty" was first applied to patients in 1824 at the S:t Bartholomew's Hospital in London, Great Britain, while "casualty department" dates back to the mid nineteenth-century according to the Short Oxford Dictionary.[3] Initially, these departments were primarily focused on casualties due to accidents. As the field of medicine expanded in the first half of the 20th century, so did the capacity to treat acute medical conditions and the scope of these departments increased beyond casualties. In Sweden, the word Emergency Department (ED) was first mentioned in 1963 according to the Swedish Academy Dictionary. Conceptually, these departments are a part of the Emergency Care System (ECS), involving initial care in the community, transport to and ED through Emergency Medical Services (EMS) and subsequent care in the hospital.

The boundaries of the ECS are not clearly defined but EDs play a central role in the provision of care for a majority of emergent and unplanned care in modern healthcare systems.[4–6] EDs provide resuscitation and stabilisation of critically ill patients as well as diagnostic resources for any patient, regardless of the type of complaint and injury, 24 hours a day every day of the year. Over the last decades there has been an increase in the number of ED attendances ED worldwide [7–10] and increased patient complexity [11,12]. The proportion of patients with advanced age and more comorbidities increases, which make both treatment and the diagnosis process more challenging and time-consuming in the ED. At the same time, the number of hospital beds have declined in all OECD-countries and the utilisation of these beds have increased.[13] In Sweden, there has been a considerable decline in the number of hospitals with EDs. From 1970 to 2016 there was a 40% decrease, from 116 to around 70.[14] The increasing demand for ED care without coordinated increases in resources causes considerable strain on EDs around the world,[15] resulting in the phenomenon of crowding which we will explore further in this thesis.

Crowding in the Emergency Department

When resources do not match the demand

Neither the Swedish Society for Emergency Medicine (SWESEM) nor the European Society for Emergency Medicine (EuSEM) have any policy statement or definition of ED Crowding. The American College of Emergency Physicians created their first policy statement on ED crowding in 2006. This statement has subsequently been updated and states that:

> "Crowding occurs when the identified need for emergency services exceeds available resources for patient care in the emergency department (ED), hospital, or both" [15]

The Royal College of Emergency Medicine (RCEM) in the United Kingdom defines crowding as:

> "the situation where the number of patients occupying the emergency department is beyond the capacity for which the emergency department is designed and resourced to manage at any one time." [16]

Australasian College for Emergency Medicine (ACEM) defines ED crowding as:

> "Emergency department overcrowding refers to the situation where ED function is impeded because the number of patients exceeds either the physical and/or staffing capacity of the ED, whether they are waiting to be seen, undergoing assessment and treatment, or waiting for departure" [17]

All definitions describe a situation where the available resources in the ED are insufficient to meet the needs of the patients in the ED. Both RCEM and ACEM further mention *the number of patients* in the ED as a key factor while ACEP defines the *need for emergency services.* Although subtle, this difference is noteworthy and conceptually interesting. Obviously, the patients create the demand for care in the ED. Thus, no patients equals no demand and consequently no crowding. Equally obvious is that a sufficiently high number of patients will eventually cause any ED to get crowded . However, the presence of relatively few but complex, high acuity patients will likely overwhelm most EDs at some point as well, particularly during low resourced periods like evenings and nights. This is likely one of the intended meanings of the "resourced to manage at any time" part of the RCEMs definition and the "or staffing capacity" addition in the ACEM statement. Focusing on the number of patients will likely capture the majority of issues related to crowding, but may miss some important situations when demand exceeds capacity.

Given the unplanned and emergent nature of the demand on an ED, it is inevitable that situations will occur when the resources do not match the demand. It would be impossible or, at least, practically unfeasible to always have the resources available for any possible event or demand. However, what has become increasingly prominent over the last three decades is that this mismatch between demand and resources have gone from an occasional phenomenon to a regular entity, if not the norm, in some healthcare systems.[7,8,18]

From occasional event to widespread phenomenon

In the beginning of 1990 the earliest published reports of ED crowding appeared from New York City in the US.[19] Although the publication was among the first, it described a city-wide problem of ED and hospital crowding with 30% of ED patients waiting for a hospital bed while hospital bed occupancy was around 96% and 90% of hospital admissions came through the ED. Such a profound demand situation was unlikely to have happened overnight and, as the authors allude to, the problem started developing during the 1980s. In 1989 ACEP arranged a conference exclusively on ED crowding, further confirming the widespread problem in the US.[19] In 1991, Lynn et al. reported the results of a survey conducted by ACEP where 41 out of 54 chapters (representing 94% of the US population) stated problems with crowding, and hence the problem was present in a significant part of the US.[20] Furthermore, 239 responding hospitals from 40 states reported ambulance diversion during parts of August 1988 with 10% of EDs reporting overcrowding, defined as patients waiting for inpatient beds every day during the survey month.[21] In the Santa Clara region in northern California, ambulance diversion due to ED or hospital crowding increased from 2.2% of all transports in 1986 to 9.1% in 1989.[22]

Outside the US, reports from Australia appeared around 2000 with Fatovich et al. describing a considerable increase in ambulance diversion episodes at the Royal Perth Hospital in Western Australia, from two episodes during a four-year period between 1996-99 to 141 between 1999-01. The majority of episodes were due to access block, where patients deemed ready for admission were waiting in the ED, or due to high number of attendances in the ED.[23] Similarly Richardson et al. described access block for 9% of ED admissions in a tertiary care center Canberra, Australia in 1999.[24] In Europe, one of the first reports by Gilligan et al. described that an average of 20 patients were waiting for a hospital bed at 09:00 with an average length of stay (LOS) in the ED of 16 hours in a large teaching hospital in Dublin, Ireland between 2004 and 2005.[25] This was more than 10 years after the first reports from the US and, indeed, the picture in Europe 2011 was somewhat more heterogeneous with reports of crowding from France, Italy and Spain, while the Netherlands, Germany, Denmark, Finland and Sweden reported limited issues with ED crowding.[18]

Looking beyond Europe, Australia and the US, ED crowding has been described as severe in India, Iran, Taiwan and Saudia Arabia while less severe in Hong Kong and Canada.[26,27] Common to most countries outside the US and Australia is that the reports cover one or a few hospitals, but data on a national level is scarce.[28–32]

In 2003, Asplin et al. described a seminal theoretical model of crowding that has shaped much of the research on crowding in the last two decades.[33] The authors propose that the process causing ED crowding can be divided into three principal components; input, throughput and output. Input encompasses the demand due to serious illness, urgency of chronic conditions and the concept of safety net care where the inability to receive appropriate, timely care somewhere else may lead to an ED visit. Throughput is governed by internal processes of the ED and will be affected by staffing, turnaround time for labs, diagnostics and imaging and are generally within the control of the ED. Output refers to the ability of the ED to discharge patients from the ED, both to admit to hospital or arrange with appropriate followup for patients discharged home or to an outpatient clinic. The paper also outlines the priorities of further research on crowding such as how to measure crowding, its causes, consequences and possible interventions.

The academic community heeded both the input-throughput-output model and the research priorities proposed by Asplin et al. Up until 2011, a total of 71 potential measures of crowding had been proposed.[34] The measures were quite evenly distributed between the input, throughput and output domains. Most common were numerical based metrics, like the number of patients in the waiting room or the ratio of patients to treatment beds in the ED as well as time-based metrics like the LOS in the ED. While multidimensional models, combining several counts or time-based metrics, was less common. In an effort to understand the clinical implications of crowding, Stang et al. found evidence of decreased quality of care associated with at least 15 different metrics of crowding.[35] In the following two sections, I outline some of the negative effects associated with ED crowding as well as the described causes.[36] Interventions have been studied to varying degrees, often in small single center studies, and will not be described in detail in this thesis.[26,36]

The negative effects of crowding

Crowding has been associated with decrease in several aspects of care quality.[35,36] This includes delays in time critical interventions like antibiotics for patients with sepsis, prolonged waiting time to surgery for patients with fractured femurs of the neck and door-to-balloon time for patients with myocardial infarction. Even though the major part of these processes reside outside the ED, the initiation of care is usually done in the ED and delays here will affect the whole chain of care. For ED-specific processes, both time to triage and time to analgesic treatment for painful conditions increase with crowding. Risk of medication errors also increase and patients are less likely to receive their ordinary medications during periods of

crowding.[36] From the patient's perspective, there is an association between high shift occupancy rates (OR), i.e a large number of patients in the ED compared with the number of treatment beds, and lower satisfaction scores.[37]

For staff working in the ED, crowding has been associated with decreased wellbeing. In a retrospective review from a level one trauma center in the US, there was an association between days of ED crowding, measured as average OR and increased violent incidents involving ED staff.[38] In a large survey of 154 ED directors in Canada, nurse workload and wellbeing was negatively affected by ED crowding.[39] Furthermore, Moskop et al. argue that ED crowding impacts the ability to provide care and therefore is a profound source of ethical stress for ED providers.[40]

Patients seldom die of crowding, but crowding may impair the ability of healthcare providers to recognize or intervene on the patient's condition. Thus, the effect of crowding is expected to be variable both between individuals and situations.[9] Nevertheless, several reports have linked ED crowding to increased short-term mortality following the ED visit. This increase in mortality has been reported for the overall patient population in the ED,[29,41–44] as well as for specific subpopulations like low acuity patients,[45] admitted patients [46–48] and high acuity patients [49].

Many of the previous studies on the negative effects of crowding are heterogeneous in their definitions and measures of crowding which makes it difficult to generalize from the results.[35,36] On the contrary, one may argue that the number of studies and different measures of crowding, in itself, speaks for the generalizability of crowding as a phenomenon between different healthcare settings. Regardless, the results indicate that crowding has a negative effect on the patients treated in the ED.

Why do Emergency Departments become crowded?

Several reports have investigated the potential causes of crowding to identify areas where interventions to alleviate the issue would be effective.[7,36] The main challenge with this type of problem is that in order to scientifically infer causality, we would need to prove causality between a phenomenon and crowding. The conventional way of doing this is to perform a randomised controlled trial where, in the context of crowding, patients would be randomised to different EDs where certain features varied and then measure the extent of crowding at each ED in relation to the outcome of the patients. This would be both unfeasible and unethical, and we thus have to build our knowledge on non-randomized, observational studies. In observational studies we analyse possible associations between different exposures and the outcome of interest. This can be done in a number of ways, but in essence the results and conclusions we can draw are limited to the factors we can measure and control for. For example, if we have 10 different features that all may contribute to crowding, but we are only able to measure 8 out of these 10 variables, there will

be uncertainty how much information is lost without the two missing variables and how these would affect the results of the other remaining eight.

Crowding is defined by a mismatch between demand and resources. Generally, it is easier to measure demand than resources. Demand is based on the need of our patients, and is registered extensively in the ED since determining the need of either treatment or diagnostic workup is the essence of what we do. Resources however, are often harder to measure. Some resources, like diagnostic investigations are shared with the rest of the hospital and may be hard to quantify from the perspective of the ED, other than turnaround time. Others, like performed treatments, depend on manual registration by the ED staff to be measurable, the same staff that will be affected by crowding. When crowding increases staff likely prioritise patient care compared to documentation, hence confounding the accuracy of these measures. Furthermore, human resources may be both difficult to quantify, due to differences between individuals in terms of knowledge and experience, and difficult to measure since scheduling is done in separate systems and may not always reflect all assigned tasks apart from seeing patients.[50] Since causality inferred from observational studies is dependent on which factors we are able to measure, the issue gets inherently difficult for ED crowding. Hence, it is not surprising that most studies on crowding deal with the effects rather than the causes.[36]

Based on the conceptual model proposed by Asplin et al.[15], causes related to input are an increased number of elderly, complex patients, high volumes of non-acute patients, limited access to primary care and other alternative diagnostic services in the community.[36] Nursing staff shortages, junior medical staff and delays in diagnostics and dispositions are throughput factors which have been associated with increased crowding, as well as problems in ancillary digital support systems.[36,51] Delays in patient transfer after an admission decision, when the patient is said to be boarding in the ED, is the primary output factor that has been shown to increase crowding in the ED.[36] The phenomenon of boarding patients in the ED[52] has received substantial attention internationally and is described as a strong contributor to crowding [53,54] with several authors arguing that it is the single most important causative factor for crowding in EDs.[42,54–56] It has been associated with decreased quality of care in asthmatic patients, decreased pain management, decreased patient satisfaction and an increase in compromised care according to providers.[35]

While boarding has been associated with decreased quality of care, the effect on inpatient mortality is variable [57] and it was not associated with increased overall ED occupancy in a large national report in the US.[7] Both RCEM [17] and ACEM [18] put emphasis on access block, patients waiting for an inpatient bed, as the major cause of ED crowding. This phenomenon is also known as exit block and causes considerable problems for EDs worldwide [36,57] but has previously not been studied in Sweden.

Measuring Crowding

Despite extensive research on both the effects and causes there is no universal criterion standard to measure crowding. According to the American Medical Association, a criterion standard in the clinical setting is a "diagnostic standard for a particular disease or condition, used as a basis of comparison for other (usually noninvasive) tests. Ideally, the sensitivity and specificity of the criterion standard for the disease should be 100%".[58] Thus, a criterion standard should represent the definition of the condition of interest - crowding - and have the capacity to identify all occurrences of crowding (no false negatives) without including situations where crowding does not exist (false positives). As outlined above, in 2011 there were 71 metrics to measure crowding,[34] and because of the lack of a criterion standard to compare with, the diversity of measures is a major problem in crowding research.[35]

The missing criterion standard

As crowding has evolved from being a problem at the local ED to an international public health issue, several organisations have identified it as a top priority for research,[53,59] and the necessity to compare and reproduce results between healthcare settings increases. Furthermore, crowding should not be seen as an ED-specific problem but rather as a hospital or system-wide issue where the causes, and thus the solutions, to decrease crowding should not be isolated to the ED only.[17] Hence, in order to address crowding both on a national, international and systems level, common standards and comparability of measures are necessary.[34]

Without a criterion standard for crowding, evaluating new metrics, or assessing the validity of accepted metrics is challenging. If you want to investigate the effect of phenomenon A (crowding) by a measure (a) on outcome B (mortality), but you have no good reference standard for A, how do you then ascertain that your measure (a) of A is valid? One way is to select a known factor of crowding as a measure of crowding (a), like the number of patients waiting for an inpatient bed (boarding due to access block). This measure may accurately identify specific situations of crowding when an access block is the main problem. However, it may miss situations of crowding where access block is not a problem. Another such measure is occupancy, i.e. the number of patients in the ED, or occupancy rate (OR) which is the number of patients divided by the number of beds in the ED.[60] Occupancy and OR, sometimes referred to as bed occupancy, have been used interchangeably in the literature.[42,44,48,61] Throughout this thesis however, occupancy alone will refer to the number of patients in the ED while OR will refer to the relation between patients and treatment beds. When looking at the conceptual model by Asplin et al.[15] these single measures focus on a certain aspect of the input-throughput-output model. One may argue that if any part of this process is affected, there will be downstream

effects for the whole system and that, as a consequence, any factor will eventually identify when crowding occurs.

An alternative approach would be to try to use a measure with the best estimation of the whole ED process as the criterion standard (A). This would, theoretically, identify different aspects of crowding but may be less specific than factors like boarding patients or OR. In the US, one common measure has been ambulance diversion, which is a state where the ED defers ambulances to other nearby EDs. This can be used as a way of decreasing the demand of care on an ED in a situation where the resources are insufficient. Ambulance diversion is expected to reflect the overall state of the ED, and it has been used by several authors as a criterion standard.[34,35,46,62] Others have used the subjective assessment of the ED staff as a standard of crowding.[63–65] This requires more resources for data collection and is therefore not suitable for continuous collection but may be used as the criterion standard of crowding (A) to evaluate new measures (a) against.

Existing methods for measuring crowding

Single Measures

Several single measures and combined measures (models) of crowding have been studied. Due to its simplicity, one of the most common measures used is OR.[34,60] It is a single measure that only requires knowledge of two variables; the number of treatment beds and the number of patients in the ED at a given time point. Data that is always readily available in the ED information system. OR has consistently been shown to be a useful estimation of crowding [60,66] and high OR has been associated with increased morbidity, mortality and decreased quality of care.[29,35,41,44]

Another well-studied measure of crowding is ED LOS, generally defined as the time from registration until physical discharge from the ED. As a simple difference between two points in time for a single patient, it is easy to measure and equally easy to calculate from the ED information systems. In a demand-resource model, as demand increases, LOS for patients will start to increase, which in turn will increase the number of patients in the ED. Increased LOS may thus be an early indicator of crowding. Although the concept of long LOS is not clearly defined and preferred LOS differs between countries (e.g four hours in the UK and Sweden but six hours in Ireland), it is generally accepted that longer LOS is worse.[67] Indeed, several studies have shown associations between increased LOS and mortality for non-critically ill patients discharged home,[43,45] critically ill patients [68] and in the general ED population[41]. Furthermore, LOS is a common measure used when evaluating interventions since it may be seen as a specific measure of ED throughput or flow, which is a common objective when seeking to improve ED operations.[69–72]

Combined Measures (models)

In 2004, Weiss et al. derived the National Emergency Department Overcrowding Score (NEDOCS) [64]. This was one of the first attempts to combine several metrics into a composite score to measure crowding. The rationale was that a combined score may have the ability to measure different aspects of crowding in the ED and detect it more accurately. For the NEDOCS model, staff perception of crowding was used as the criterion standard and several ED metrics were screened and selected by regression analysis for their accuracy in approximating the staff's assessments. The end result was a model combining five variables (Table 1).

Table 1: Variables in the National Emergency Department Overcrowding Scale

Variable	Description
Patient Index	number of ED beds / number of hospital beds
Ventilators	number of patients in the ED / patients on ventilators in the ED
Admit Index	number of patients waiting for an inpatient bed
Admit Time	waiting time of the patient waiting longest for an inpatient bed
Registration Time	the longest waiting time for a patient in the waiting room

The model returns a score from 0 to 200 where 101 - 140 is considered overcrowded, 141-180 severely overcrowded and >180 dangerously overcrowded. NEDOCS showed good correlation with staff's assessment of crowding in the derivation study based on the coefficient of determination ($r^2=0.49$). It has subsequently been validated in several different settings and constantly shown good predictive ability with AuROC=0.92 and 0.80 [66,73] and r=0.78 [74] for staff perception of crowding.

Around the same time that NEDOCS was derived, another model named the Emergency Department Work Index (EDWIN) was developed by Bernstein et al.[63] This model was derived with staff assessment of crowding as the criterion standard for crowding. This model of crowding puts demand for care in relation to the available resources, which is uncommon in combined measures of crowding. Specifically, EDWIN accounts for the number of physicians and treatment beds in the ED. The model is calculated by the formula:

$$EDWIN = \sum \ n_i t_i / N_a (B_t - B_A)$$

The numerator is the sum of products of the number of patients (n) by triage score (t) for each triage score (i) from one to five with five being most acute. The denominator is the number of attending physicians N_a multiplied by the number of treatment beds B_t subtracted by the number of beds occupied by a patient waiting for an inpatient bed B_A. The model had a strong association with the staff's perception of crowding and ambulance diversion in the derivation study.[63] It has been validated in several studies with AuROC scores ranging from 0.80 to 0.86 for staff assessment of crowding [66,73] and 0.81 for ambulance diversion [62].

More than a decade later, Boyle et al. published the first model derived outside the US.[65] The International Crowding Measure in Emergency Departments (ICMED) was developed in the UK with ED consultants' perception of crowding and danger as the criterion standard. The authors used a delphi survey method to agree upon several metrics that represented different aspects of ED care relevant to crowding in conjunction with the input-throughput-output model.[75] A total of eight variables were included in the model (Table 2).

Table 2: The variables included in the International Crowding Measure in Emergency Departments (ICMED)

Variable	Violation threshold	Domain
Ability of ambulances to offload patients	An ED is crowded when the 90th centile time between ambulance arrival and offload is greater than 15 min	Input
Patients who leave without being seen or treated (LWBS)	An ED is crowded when the number of patients who LWBS is greater than or equal to 5%	Input
Time until triage	An ED is crowded when there is a delay greater than 5 min from patient arrival to begin their initial triage	Input
ED occupancy rate	An ED is crowded when the occupancy rate is greater than 100%	Throughput
Patients' total length of stay in the ED	An ED is crowded when the 90th centile patient's total length of stay is greater than 4 h.	Throughput
Time until a physician first sees the patient	An ED is crowded when an emergent (one or two) patient waits longer than 30 min to be seen by a physician	Throughput
ED boarding time	An ED is crowded when less than 90% of patients have left the ED 2 h after the admission decision	Output
Number of patients boarding in the ED	Boarders are defined as admitted patients waiting to be placed in an inpatient bed. An ED is crowded when there is greater than 10% occupancy of boarders in the ED	Output

Rather than scoring each variable in a continuous fashion, the variables are scored dichotomously and counted when violating a specific threshold for each variable, yielding a maximum score of eight. The model showed good discriminatory value (AuROC 0.80) and correlation (Spearman rho=0.60) against ED consultants' assessment of crowding with a suggested score of three to identify crowding with high sensitivity (0.91) and specificity (1.00). It was externally validated with minor modifications to account for differences in data acquisition between EDs. The model correlated with staff's assessment of crowding in seven EDs in five different countries but the results were variable compared to the initial derivation and validation, with Spearman rho ranging from 0.01 to 0.76.[74,76]

Additional models or combinations of different metrics have been published, like the Demand Value of the Real-time Emergency Analysis of Demand Indicators (READi)[66] and Emergency Department Work Score (EDWS)[73] but have not been as extensively studied as the abovementioned. Although NEDOCS consistently performs well in the studies in which it has been validated, it is not possible to determine which of the above models is best suitable to measure crowding. EDWIN has the advantage of quantifying resources as well as demand through the number

of attending physicians. However, the uptake of NEDOCS has been larger compared to EDWIN, possibly due to the difficulty and measuring physician coverage. ICMED has been externally validated but the variable results still pose questions of its generalizability to other settings.

Emergency departments and crowding in Sweden

In Sweden, as in most countries, the Emergency Department is a fundamental part of the ECS.[4,14] Historically there have been two conceptual models of how to organise the ECS in Europe, the anglo-saxon and the franco-german model.[77,78] In the anglo-saxon, patients have been rapidly transported from the community, with minimal intervention, to a highly capable and resourced ED by EMS with basic medical training. While in the franco-german system more resources and education have been focused on the community through primary care physicians and advanced providers in the EMS, that have had the ability to treat, or initiate advanced treatment, in the field. Consequently there has been less emphasis on the experience of physicians in the ED which have primarily been junior physicians with on-call subspecialists. Most systems exist on the spectrum between these descriptions, which affects the governance of EDs within the system. In Sweden, the ECS has been organised similarly to the franco-german model where emphasis has been on the initiation and management of care in the community rather than in the hospital.[14]

Up until the large "Seven Crown Reform" in Sweden 1970, EDs and hospital-based urgent care offices were staffed by senior physicians from different in-hospital specialties. Patients had been paying the physician directly for the visit and then applied to the ministry of social security for a partial refund of the cost. After the reform, patients paid only a minor proportion of the visit fee directly to the institution, which employed the physicians. The institution was then reimbursed from the ministry for social security. When physicians salaries were paid by the employer instead of the patient, the previous large monetary incentive for a high volume of outpatient care disappeared. Although seemingly of limited importance, this reform turned out to be a milestone for the provision of care in Sweden.[79] Subsequently the number of frontline senior physicians declined and was replaced by junior doctors. Consultants or senior physicians were instead available on an on-demand basis, usually via telephone, and the vast majority of ED physicians were just rotating through the department.[14] However, as the field of medicine has progressed, so has the complexity of the conditions and treatments of patients that are brought to the ED.[11,15] This apparent mismatch between patient complexity and physician training was one of the reasons for the initiative to move towards a more anglo-saxon model for emergency medicine in Sweden. It started with the creation of the Swedish Society of Emergency Medicine (SWESEM) in 1999.

In 2006 the Swedish board of Health and Welfare added Emergency Medicine (EM) as an add-on speciality to the formal medical training in Sweden, and EM then

became a freestanding speciality in 2015. The most recent and comprehensive overview of Swedish EDs governance and staffing in 2018 found that 65% of the 57 responding EDs have faculty physicians but that almost all (54/57) still also relied on physicians from other departments.[14] EM specialist physicians were present, or available for consulting, at 50% of the EDs but only one ED was solely staffed by consultants or residents in EM. Even so, a 50% basic coverage 15 years after the recognition of EM as a subspeciality is evidence of progress. With consultants in EM, the number of faculty physicians in Swedish EDs is likely to keep increasing and with it the possibility for more coherent and continuous research and development.

Historically, much like in other parts of the world, crowding has been a limited problem in Swedish EDs.[19] However, increased attention was directed to the state of the EDs around 2010 when there were several media reports about strained ED working environments throughout Sweden. News articles were frequently published with testimonies of extreme demands on the health care staff who felt helpless in a situation where resources were insufficient. However, little data existed on the overall state of EDs in Sweden at that time. Despite a longstanding tradition of high quality patient registries, there have been no specific registry for ED patients until recently,[80] limiting the overview of EM in Sweden. The national board of health and welfare has published a few reports on the state with process data limited to length of stay and waiting times.[81,82] However, a vocabulary for crowding, as well as initiatives to systematically measure or address the demand and resource imbalance, has been lacking. With ED crowding as a potential emerging problem in Sweden, it was therefore essential to initiate research on the topic.

Aim

The aim of this thesis was to provide a scientific base for crowding research in Sweden. Specifically we aimed to derive and validate a measure for crowding that was possible to implement nationally, was reproducible between institutions and had the capacity to identify situations when crowding affects our patients. Further, we wanted to compare the proposed model to international models of crowding and investigate the prevalence of crowding on a national level in Sweden.

The aim of the specific studies in the thesis were the following:

I: To derive and validate a predictive model to measure crowding based on workload in Swedish EDs, independent of ED size and hospital type.

II: To study the prevalence of crowding on a national level in Sweden, both in terms of demand and resources.

III: Investigate the differences between crowding measured by the combined model from paper I and and a single measure, specifically OR.

IV: To investigate whether crowding, measured by the model from paper I can detect an association between crowding and increased all cause mortality for ED patients.

Methods

With no validated measure of crowding in Sweden, nor any systematic attempt to estimate the prevalence of crowding outside of the national board of health and welfare reports on waiting times,[81,82] our first goal was to address the issue of measuring crowding. We decided to derive a multidimensional model, trying to combine several metrics representing the theoretical input-throughput-output model.[15] Although previous studies had shown limited benefit compared to single measures like OR or LOS,[34,60] the potential to better detect different aspects of ED crowding with a multidimensional model was prioritized. Another important aspect was the ability to use the model regardless of ED size and hospital type.[83] Thus we planned to derive the model in a diverse hospital setting.[34] Additionally, to facilitate automatic measurements, we excluded variables that required data which was unavailable in the electronic ED information systems.[83] This prerequisite was important as we believed that manual input would be a barrier for using the model in the clinical setting, reducing feasibility and cost effectiveness.[84]

At the outset of this thesis, NEDOCS and EDWIN were the multidimensional models with most scientific evidence and evaluation.[34,63,64] However, the generalizability of these models to the Swedish ED setting was uncertain. NEDOCS had been derived at academic EDs and incorporated the number of patients on ventilators in the ED. Patients may be intubated in the ED in Sweden, but initiating ventilator treatment is rare and always made in close cooperation with intensive care, and patients never stay in the ED when intubated. Although the impact of the *ventilator* variable on the total NEDOCS score is marginal (up to 20 of total 200), it still posed a problem for generalisability.

For the EDWIN score, an essential factor is the number of attending physicians on duty,[63] which is difficult to calculate in a majority of Swedish EDs. To a large extent, historically as well as currently, the workforce in Swedish EDs include physicians in training; interns and registrars of different subspecialties. In the most recent report from the Swedish Agency for Health and Care Services Analyses, 40% of responding EDs reported periods where the ED was staffed solely by interns or physicians in training. Attending physicians are present at almost all large academic and urban centers during the day, but not always during the night.[14] Community and rural EDs may only have attending physicians available through phone consultation. Additionally, attending physicians may have combined positions in the ED and emergency wards, and all these things made the EDWIN score hard to calculate.

Further, staffing numbers are rarely registered in a fashion that allows automatic measurements.[14] Since the goal of our measure was to automatically measure crowding prospectively and retrospectively, EDWIN was deemed unsuitable as our primary measure of crowding.

Given these concerns with the established international models, we decided to derive a model customized for Swedish EDs in the initial stage and then validate and benchmark it against NEDOCS as well as simpler measures like ED OR.[34,60]

Choosing a criterion standard

Although the definitions of ED crowding are similar between the large organisational bodies,[16–18] there is no consensus of how to best measure crowding.[34] However, to develop a model, a standard for crowding is needed. We choose staff's perception of workload as the criterion standard for crowding that we would evaluate our model against. As outlined above, staff perception has been used in several other studies and has been shown to correlate well with other aspects of crowding.[63–65] Our hypothesis was that this was the best surrogate with a potential to encompass different aspects of crowding, both increased demand and limited resources. The term *workload* was chosen because the corresponding word in Swedish was the conventional term that had been used within the professional society and in the community to describe the phenomenon of ED crowding. The swedish translation of *crowding* is a word which is seldom or never used in the health care setting in Sweden. Thus, rather than trying to introduce new terminology, we decided to use the established term. Furthermore, the primary focus of the research on crowding is to reduce its impact on quality of care for our patients. It is reasonable to believe that many of the described negative effects of crowding on patient care is mediated through high workload.[35]

Modelling crowding

The process to develop a prediction model in medicine is commonly divided into three phases; derivation, validation and implementation, or impact.[85] The derivation phase is where a set of variables for the potential model are selected and tested against the criterion standard or outcome of interest. One or more variables that show predictive value in the estimation of the criterion standard are then combined into a model. This selection and prediction process is most often done through regression analysis, which is a type of basic machine learning where variables are tested and excluded if their predictive value cannot be statistically ascertained.[86] The result of this selection may be any combination of variables that fitted the regression

analysis, and variables that have a rationale to affect crowding may have been filtered out. When inspecting the combination of variables in a predictive model it is important to understand that it is not necessarily the only variables explaining the outcome of interest. This is in contrast to a *descriptive model*, where you are interested in any variable that can add value in understanding the causes of the outcome, even though the predictive value of the variable may be limited. Selection of variables is hence seldom done for this type of model.

The second phase after derivation of the model is validation, where the model is tested on a separate dataset to establish that the results from the derivation was not just pure chance or limited to the initial dataset.[85] This phase is commonly divided into internal and external validation where internal validation may be done on a separate dataset from the same hospital or a subset of the initial dataset, while an external validation is done to test the generalisability of the model by validating it in a setting separate from the one used in the derivation. This may be in another hospital, another country and preferably by another author group.

Finally the model should be evaluated in an implementation phase, or an impact analysis, to establish how the model affects the environment in which it is used. This phase is important to study whether the model has the intended effect, as well as any non-intended effects, when using the model.[87] To our knowledge, few models of crowding have been studied in an implementation phase.

Paper I – Creating a model

The first phase was done in Paper I where we derived a model at 5 different EDs in the county of Skåne in Sweden. The EDs were diverse in size and type with two being large academic tertiary care EDs, two being urban community EDs and one a rural community ED. The nurse and physician in charge assessed workload on a Likert scale with anchors [88] from one (no workload) to six (very high workload) at 50 different time points during a three week period. The time points were randomised from prespecified hours during the day (02:00, 08:00, 12:00, 16:00, 20:00, 23:00) for each ED during the time period. The hours were chosen to represent periods with low and high levels of crowding with sufficient time between to limit temporal correlation between assessments[74,89] and make collection feasible. The assessment was averaged between the two assessors at each timepoint. Randomization was done to reduce the risk of bias, by not asking all EDs at the same time point, or the same providers at repeated time points.

Data to calculate all candidate variables for the model were extracted from the ED information system at the same time point. The chosen variables had been selected based on prior literature in discussions with senior emergency physicians and slightly modified to account for differences in ED size. A model was created using linear regression with stepwise backward selection of predictive variables with the

averaged assessment of crowding as the independent variable. The final model from the derivation included the variables *Patient Hours, Time waiting for physician, Occupancy Rate and High Acuity Patients* (Table 3).

Table 3: Variables included in the Skåne Emergency Department of Patient Load score

Variable	Description
Patient hours	The sum of time, in hours, that all patients spent in the ED during the previous hour, divided by the average daily ED census.
Awaiting MD	The time spent waiting for a physician after initial triage divided by the number of patients in the ED.
Occupancy rate (OR)	The number of patients in the ED divided by the number of treatment beds.
High acuity patients	The number of high acuity patients (highest and second highest triage level) divided by the total number of patients in the ED.

A separate dataset was collected to internally validate the model from two of the included EDs, during two and three weeks respectively, when all nurses, physicians and assistant nurses present at each time point were asked to assess their workload. The staff's average workload at each timepoint was correlated with the models predicted score. In this data collection we asked all clinical staff, compared to the nurse and physician in charge in the derivation, to validate the models ability to predict the assessed crowding and whether the nurse and physicians in carge's assessment could be transferable to all clinical staff.

Crowding in Sweden

Paper II – A national point prevalence study

This was a cross sectional study where we sought to assess the prevalence of crowding on a national level in Sweden since existing data on the current state of crowding in Sweden is limited to waiting times and census.[81] All Swedish EDs listed in the national healthcare institution registry (HSA) were offered to participate by email to the head of department, followed by a telephone call. Participation was confirmed in writing by the department head.

At five predefined time points (00:00, 06:00, 12:00, 18:00, 23:59) during 24 hours all EDs collected data on the number of patients, nurses, enrolled nurses, physicians, ED workload (one - no workload, six -very high workload) and number of patients waiting for an inpatient bed. Additionally we collected hospital status, daily ED census, annual ED census and number of treatment beds in the ED. When counting physicians we did not differentiate between interns, registrars or consultants. Workload was assessed by a senior staff member of the ED but it was left up to the ED to decide who did the assessment. A boarding patient was defined as a patient

with a decision for admission who was still present in the ED, regardless of the duration since the decision had been made. Crowding was defined as an OR above 1.0 i.e. more patients in the ED than treatment beds or an assessed workload higher than 4.5. Additionally, we investigated the working staff's patient load by reporting the patient to provider ratio for enrolled nurses, nurses and physicians respectively.

Paper III - Comparability of crowding measures between EDs

This paper used the dataset acquired with the methodology described for paper II and dealt specifically with the comparability of OR and workload between EDs. From this dataset we observed considerable differences in both OR and the number of treatment beds in relation to daily census between EDs. We wanted to test the hypothesis that there were baseline differences in the number of treatment beds in relation to ED census and whether this difference would influence the OR metrics in addition to the demand for care between EDs.

To test this, we calculated the turnover per treatment bed (TTB), defined as the ratio of the number of treatment beds to the average daily census for each ED. We compared OR and workload between EDs with high TTB, defined as a TTB above the mean, and low TTB. We used a mixed effects linear regression model to test the effect of TTB on crowding, adjusting for OR, hospital type, assessment time and staffing. The mixed linear model was chosen to account for repeated measures for each ED.

Effect on our patients

Paper IV – Measuring negative effects of crowding

The criterion standard for crowding that we used to derive and test our model in paper I was staff assessment of crowding. Although the results of paper I suggest that the SEAL model is a valid and reproducible measure for this metric, it was unknown whether the model could identify situations when crowding affects patient outcome, specifically increased mortality. We used the modified SEAL (mSEAL) score derived by Wretborn et al. to be able to calculate crowding from the Swedish quality registry for Emergency Medicine (SVAR).[80,90] The mSEAL score encompasses two variables compared to four the SEAL model; *patients hours* which is common to both models and *time to physician* which is the time from registration to first physician contact. The model has been shown to perform similarly to the SEAL model but with the advantage of using less data from the ED information system.[90]

To study whether the mSEAL model could predict mortality, we retrospectively collected data on patients visits at six EDs in two healthcare systems in Sweden between 2017-01-01 and 2017-06-30. Process data from the ED information system was matched with data from SVAR which includes data on patient mortality. We calculated the mSEAL score and OR on patient arrival to the ED as two different exposures of crowding. OR was used as an alternative definition of crowding to test the robustness of the results. And to try and reproduce the recently published results from another healthcare system in Sweden where af Ugglas found an increased risk of mortality at 30 days during shifts with OR above the 95 centile, adjusted for shift, calendar day and hospital.[41]

The primary outcome in our study was mortality censored at seven days. At the time of designing the study there was limited published evidence on the association between crowding and mortality. One study from Canada suggested that mortality within seven days increased with increasing length of ED stay.[43] Both mSEAL and OR were stratified to account for differences in crowding depending on ED and time.[44,91,92] Each exposure was divided into four different groups. A non-crowded group, defined as an OR or mSEAL below the 85th percentile, stratified by ED and time. This group was used as reference and was compared to the 85-90 th, 90-95th and >95th percentile groups that represented increasing levels of crowding. The choice of groups was based on the hypothesis that the negative effects of crowding, in particular the severe effects like mortality, occur in a non-linear relation to crowding. Staff are likely to be able to compensate when crowding increases by prioritizing both patients and interventions to optimize effect but will be insufficient at the severe levels of crowding. This non-linear effect is supported by the recent study by af Ugglas et al. that found an increased hazard for 30-day mortality at the highest five centiles of crowding while no increase in the 75-95 centile group, compared to the < 75 centile.[41]

Statistics

Normally distributed data was described with mean and standard deviation (SD) while non-normally distributed data was reported as median with interquartile ranges (IQR). Correlation was reported with Pearson's coefficient of correlation (r) or the correlation of determination (r^2) with general qualitative descriptions.[93]

In paper I, ordinary least square linear regression was used to derive a predictive model of staff's crowding assessment. Student's t-test was used to compare means.

In paper II, correlations were assessed using ordinary least-squares linear regression. Medians were compared by calculating the grand median for each group, creating a two by two table and applying Fisher's exact test on the groups. Staffing ratios were compared using parametric ANOVA and post-hoc testing with t-test.

Boarding was compared using Kruskal-Wallis test with post-hoc testing using Mann-Whitney-U. The Holm method was used to adjust for multiple comparisons.[94]

To account for dependent samplings at each ED in paper III we used a linear mixed effects model, grouped by ED. We adjusted for OR, turnover per treatment bed (TTB), assessment time point, hospital type and staff to patient ratio. Assessment at 06:00 was used as a reference for the time point variable, and for hospital type, rural hospital was used as reference. To account for the collinearity between OR and TTB, an interaction variable was created as OR*TTB and added as a covariable to the model. The Holm method was used to adjust for multiple comparisons.[94]

In paper IV mortality within seven days was calculated using the cox proportional hazard model adjusted for age, sex, hospital admission, acuity, chief complaint and EMS arrival.

A point estimate with 95% confidence intervals not including 1.0 and a p-value less than 0.05 were defined as statistically significant.

Statistical software

In the first paper, I used IBM SPSS version 21 (IBM Corporation, NY, US) for all statistical analysis. For paper II-IV, I used the python programming language with the numpy [95] and pandas [96] library for data cleaning and management. For statistical analysis I used the scipy,[95,97] statsmodels [98] and lifelines [99] libraries. All python related software are open source and less common within the medical research field, but there is extensive experience and usage within other fields of science, like physics.[97]

Ethical considerations

The present thesis and all included studies were conducted in accordance with The Declaration of Helsinki with the utmost care for the integrity and security of the data collected.[100]

For paper I and IV we used retrospective registry data with age, arrival time, arrival by ambulance, date of death and chief complaint as possible identifiable features. However, there is not sufficient information within the collected datasets alone to identify a specific individual without having access to the original ED information system database. Even so, the datasets contain sensitive information and were handled and stored to digitally and physically minimize the risk of compromise and to respect each individual's integrity.

Staff's assessment of workload was collected and analyzed anonymously with no obligation to participate and the possibility to opt out at any given time point during the study. Although anonymously collected, only two persons were approached at each time point in paper I, the charge nurse and physician. Knowing the work schedule would allow for identification of the individual making the assessment. However the assessment time points were randomized and I was the only one with knowledge of the individual assessments and time points, while I had no knowledge of the scheduling. Limiting any potential misuse or selection bias.

Table 4: Ethical permits within the thesis

Paper	Data	Permit
I	Staff assessments, anonymous patient data (timestamps, age, acuity, chief complaint)	Permit waived
II	Staff assessment, anonymous group data (number of patients, number of patients boarding, staff numbers)	Linköping - 2018/50-31
III	Staff assessment, anonymous group data (number of patients, number of patients boarding, staff numbers)	Linköping - 2018/50-31
IV	Anonymous patient data (timestamps, age, death date, acuity, chief complaint, comorbidities)	Skåne – 2016/69

All results were analysed on a group level and although there was a theoretical possibility to identify patients or staff as described above, it was impossible with only the data obtained for this research. Ethical permit was waived by the ethical review board for paper I while permits were obtained for paper IV by the regional ethics committee of Skåne.

No individual patient or provider data was collected for Paper II and III, and these studies were approved by the regional ethics review board in Linköping, Sweden.

Results

Development of a model to measure crowding (paper I)

In the first study, our aim was to develop a model that could be used in any Swedish ED, and preferable in EDs outside Sweden, regardless of size and type. Secondly the model should not be dependent on manual input but be extractable from the ED information system. To fulfill these prerequisites, we included two rural, one urban and two tertiary care academic centers in the initial derivation phase. In this phase we matched assessments of crowding against a set of candidate variables to create a composite model.

We randomly selected 50 time points by computer generation for each ED over a period of three weeks. This corresponded to 40% of possible time points during this period. Out of 250 time points, 197 (79%) were assessed by both the charge nurse and physician, and another 36 (14%) by one of them.

The fraction of complete assessments were equally distributed Monday through Sunday as well as over the different time points of the day. Both nurse and physician assessment scores were normally distributed. The correlation between the nurse and physician scores was $r^2=0.407$ (p<0.0001). Physicians assessed the workload somewhat higher than nurses, with average scores of 3.32 and 3.19 respectively (p = 0.75).

A composite model using the variables *patient hours, high priority, awaiting MD* and *OR* explained 96.4 % of the variation compared to a model with all 14 candidate variables (Table 5), based on the coefficient of determination, with good correlation to the assessed workload($r^2=0.51$, p<0.001, Figure 1). The correlation was considerably better compared to OR alone ($r^2=0.33$, p<0.001). This model was named Skåne Emergency Department Assessment of Patient Load (SEAL).

Table 5. List of analyzed variables in the derivation regression of the Skåne Emergency Department Assessment of Patient Load.

Variable	B	95% CI	p	Measure
Priority	-0.30	-0.79 - 0.19	0.23	Average priority for all patients in the ED
Triage priority	-0.16	-0.58 - 0.27	0.48	Average initial priority as assessed in triage for all patients in the ED
High priority	*1.80*	*0.39 - 3.21*	*0.01*	*Ratio; high priority patients (n, 1 and 2) by patients(n) in the ED*
Awaiting MD	*1.39*	*0.58 - 2.21*	*0.001*	*Ratio; total time patients spent waiting for a physician by the number of patients in the ED*
Average time	0.06	0.02 - 0.14	0.13	Average time in hours spent in the ED by patients discharged
Longest stay	0.01	-0.03 - 0.04	0.79	Longest stay for any patient in the ED
Patient hours	*14.72*	*11.12 - 18.34*	*<0.001*	*Ratio; total time, in hours, spent by all patients in the ED during the previous hour by daily census*
Occupancy rate†	*-1.10*	*-1.79 - -0.41*	*0.002*	*Ratio; patients (n) in the ED by ED beds (n)*
Delta Occupancy*	0.25	-1.01 - 1.58	0.72	Ratio; new patients (n) during the previous hour by ED beds (n)
Average volume	-1.48	-12.40 - 9.48	0.79	Ratio; patients(n) by daily census
Admit index	0.95	-26.3 - 28.2	0.95	Ratio; boarding patients(n) by hospital beds (n)
Unseen	-0.17	-1.50 - 1.72	0.81	Ratio; patients no seen by a physician (n) by treatment beds (n)
MDs	-0.55	-1.92 - 0.83	0.43	Ratio; physicians (n) by patients (n)
Nurses	-0.57	-1.84 - 0.70	0.81	Ratio; nurses (n) by patients (n)

† Occupancy in the original manuscript
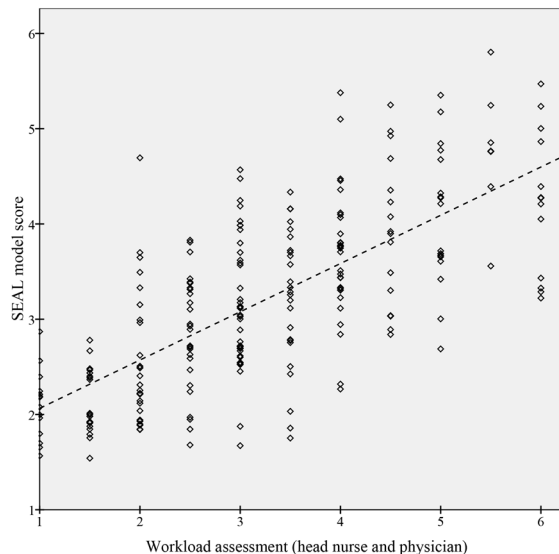
* Occupancy Rate in the original manuscript

Figure 1: Correlation between workload assessment by the nurse and physician in charge and the Skåne Emergency Department Assessment of Patient Load (SEAL) score.

Internal validation

To validate the results of the derivation, workload assessments were collected from Lund and Malmö ED during two and three weeks respectively. At Lund, 91% (32/35) of the predefined time points assessed by staff and 70% (49/72) in Malmö. A total of 526 and 369 assessments from all nurses and physicians, respectively. There was good correlation between the predicted score of the SEAL model and the assessed workload (Table 6). Correlations between the assessments of the head staff and all staff was poor in one hospital (r^2=0.16, p=0.04) and moderate at the other (r^2=0.36, p<0.01).

Table 6: Pearson correlation between SEAL model and workload assessment in the collected dataset

Dataset	Correlation variable	r^2	p	N
Primary dataset	Full model (14 variables)	0.96	<0.001	250
	Assessment of head staff	0.51	<0.001	233
Validation ED1	Assessment of all staff	0.64	<0.001	32
Validation ED2	Assessment of all staff	0.62	<0.001	49

The results of paper I suggest that it was possible to estimate ED crowding, as assessed by the clinical staff, by using data from the ED information system. We propose a model based on the number of patients, their priority and their time spent in the ED during the previous hour and the time waiting for a physician as a measure of crowding.

Prevalence of crowding and boarding (Paper II)

Prior to the start of this thesis, it was hard to obtain detailed information about the state of crowding in Swedish EDs and whether it was a problem. Reports of crowding in Swedish EDs were limited to single media reports and irregular papers by the ministry for Health and Welfare.[81,82] The media reports were limited to single institutions and occasional events rather than systematic overviews. Although the reports from the ministry of Health and Welfare were systematic and covered most EDs in Sweden, they primarily studied time-based metrics, like waiting times, averaged over months or years [81,82] which prevented insights on crowding [91]. In paper III where we wanted to investigate the extent of crowding on a national level in Sweden. Our focus was to cover as many EDs in Sweden as possible rather than following a few EDs over time, since data suggest that crowding may vary between rural, urban and academic EDs, where the latter two have shown to have higher levels of crowding.[9] We used staff assessment of workload over 4.5 (on a scale from 1 to 6) or an OR over 1.0 as a definition of crowding for crowding. In addition, we

collected the number of patients waiting in the ED for an inpatient bed (boarding) as an additional measure of crowding.[34,60,101]

Data was acquired from 37 out of 72 (51%) eligible EDs in Sweden. Crowding, defined as an OR > 1.0, occurred in 12 EDs (37.5 %) on 31 out of 170 (18.2%) time points. Mean OR was higher in academic EDs compared to rural EDs (0.83 vs 0.46, difference 0.37, 95% CI 0.16-0.58, p<0.001) and in urban compared to rural EDs (0.70 vs 0.46, difference 0.24, 95%CI 0.016-0.48, p=0.037), but there was no significant difference between academic and urban centres (p=0.45) (Figure 2). Overall workload was 2.65 (±1.25) with 14 out of 170 timepoints (8.2%) in the highest quartile. Boarding was more prevalent in academic EDs compared to rural EDs, with a median boarding of 3 (IQR 1-4) and 0 (IQR 0-1) patients, respectively (p=0.008). There was no significant difference between urban EDs (median 1, IQ 0-2) and rural or academic EDs (Figure 3).

The number of patients per provider was similar over the course of the day, except for 06:00 which was lower, with an average of 2.6 (±1.6), 4.6 (±3.1) and 3.2 (±2.2) patients per nurse, enrolled nurse and physician respectively. There were more patients per provider in academic hospitals compared to rural hospitals for both nurses (4.4 vs 2.2, p=0.02) and physicians (4.4 vs 2.6, p=0.01). Urban hospitals had staffing ratios in between rural and academic hospitals with 3.2 patients per nurse and 3.3 patients per physicians but there was no statistical difference compared to academic or rural hospitals.

Crowding measured as OR and assessed workload was prevalent in several EDs in Sweden during this 24 hour cross sectional study. High OR was more prevalent in academic tertiary care centers and urban centers compared to rural EDs and boarding was more prevalent in academic centers.
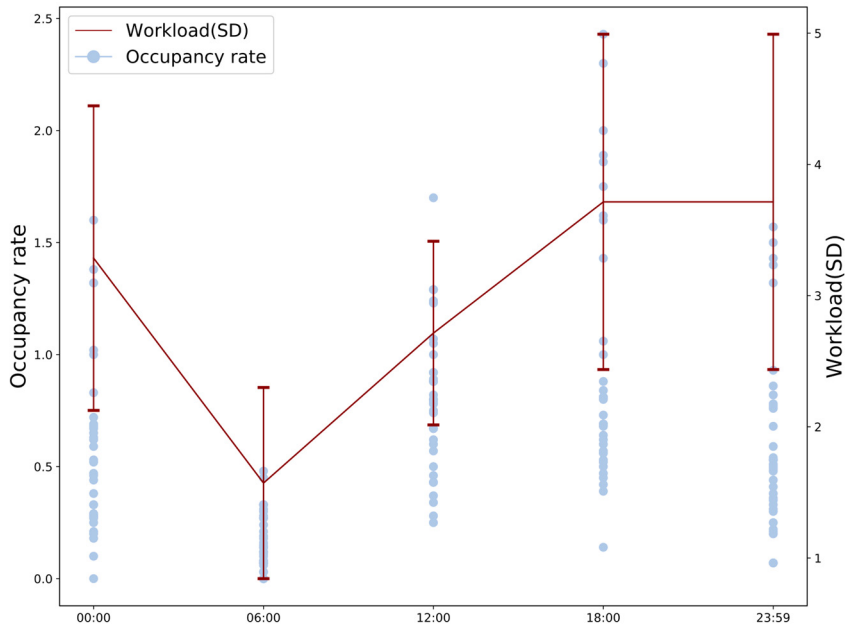
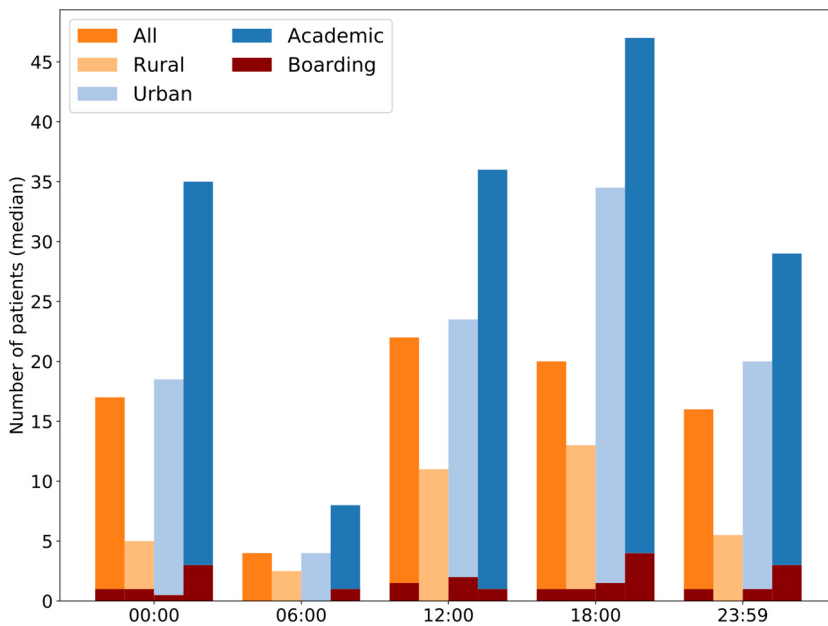**Figure 2: Occupancy rate in relation to workload at each timepoint**

Figure 3: Number of patients present and boarding in the ED, grouped by hospital type at each timepoint

Differentiating properties between workload and occupancy rate (Paper III)

In paper I-II we used OR as an alternative measure of crowding in addition to staff assessment of workload. OR, the ratio between the number of present patients and number of treatment beds has been shown to estimate crowding well in several studies.[60,91,102] When analyzing the correlation between workload assessments and OR in paper II, on the prevalence of crowding, there appeared to be two different groups of EDs (Figure 4). There was one group of EDs with high OR where the staff-assessed workload seemed disproportionate to the OR. In this group, workload was similar to that in the other group of EDs but had considerably higher OR. In paper III, we investigated this further with the hypothesis that baseline differences in the number of treatment beds contributed to this variability in OR.

To test this hypothesis we defined the turnover per treatment bed (TTB) as the ratio between the daily ED census and the number of treatment beds. The TTB varied between 2.1 patients per bed per day, at the ED with the largest number of beds in relation to daily census, to 9.2 patients per bed per day at the opposite end of the spectrum. When dichotomizing EDs to above or below mean TTB, the high TTB EDs had an average OR twice as high as the low TTB EDs (0.86 vs 0.43, diff: 0.43, 95%CI: 0.27 - 0.59, p < 0.001). However, there was no statically or clinically significant difference in average workload between EDs with high and low TTB, 2.75 vs 2.52 (diff: 0.23, 95%CI -0.19 - 0.64, p=0.22).
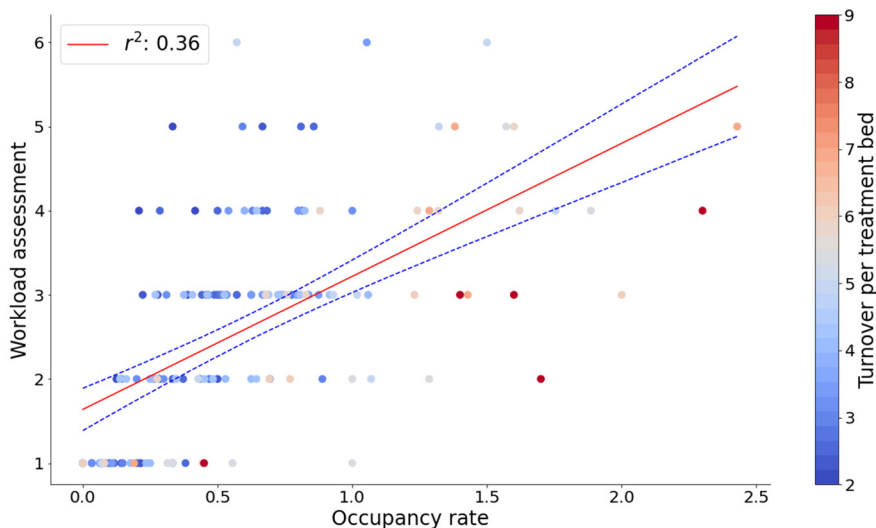

Figure 4: Correlation between Occupancy rate and assessed workload with color indicating ED turnover per treatment bed (TTB).

In a mixed effects linear regression model, assessment time point, OR and nurse to patient ratio significantly affected the assessed workload (Table 7). The odds ratio for the interaction variable of OR and high TTB was 0.60 (p=0.15, 95%CI 0.3 - 1.21), suggesting that at similar OR, staff at EDs with high TTB assessed workload lower than staff at EDs with low turnover. However the confidence intervals crossed 1 so the results were not statistically significant.

Table 7: Mixed effect linear regression model on staff assessed workload with odds ratios and 95% confidence intervals for each variable

	Odds ratio (95% CI)	*p*	*p†*
Time point			
0:00	1.52 (0.99 - 2.35)	0.06	0.35
12:00	1.85 (1.13 - 3.02)	0.01	0.12
18:00	1.73 (1.02 - 2.96)	0.04	0.31
23:59	1.83 (1.17 - 2.89)	0.01	0.10
Hospital type			
Community	1.1 (0.64 - 1.88)	0.74	1.00
Academic	1.03 (0.55 - 1.91)	0.93	1.00
Patients per provider			
Nurse	1.28 (1.06 - 1.53)	0.01	0.10
Physician	1.01 (0.92 - 1.12)	0.83	1.00
Patients			
Occupancy Rate (OR)	3.51 (1.41 - 8.7)	0.01	0.08
High Census per Treatment Bed (TTB)	1.03 (0.54 - 1.98)	0.92	1.00
Interaction (OR*TTB)	0.6 (0.3 - 1.21)	0.15	0.76
Intercept	2.31 (1.47 - 3.63)	0.00	0.00
Group Variable	1.58 (1.08 - 2.32)	0.02	0.15

† Adjusted according to Holm et al.[94]

Baseline differences in the number of treatment beds, described as TTB, may explain some of the observed differences between OR and workload. This type of difference is important to account for when using OR as a metric for crowding in different EDs.

The association between crowding and mortality (Paper IV)

Although measuring ED crowding is an interesting academic exercise, its effect on our patients is our primary interest. Several studies have shown the crowding is associated with decreased quality of care, including increased mortality.[35] Although few studies have been conducted in Sweden, a few recent papers have shown an association between crowding and mortality.[41,45] Furthermore, this association has been shown both for admitted patients in the US and for the general ED population in South Korea, New Zealand and Canada.[29,41–43,46] Thus, crowding likely has negative effects on patient mortality, both in Sweden and internationally. A potential crowding measure, like the mSEAL, should be able to identify these negative effects to be useful in ED operations management. Consequently, in paper IV, we aimed to investigate whether crowding measured with the mSEAL model is associated with increased mortality.

We collected data on 170 000 visits made by 132 000 patients to six EDs in two different healthcare regions in Sweden. 7-day mortality varied from 0.8% to 1.2% between the EDs. Using a Cox proportional hazard ratio (HR) model, crowding defined as mSEAL above the 95th centile was associated with increased HR for 7-day mortality, HR=1.05 (95% CI 1.03 - 1.18). For OR, the results were similar with a HR of 1.08 (95% CI: 1.08 - 1.24). For both mSEAL and OR, HR was also increased in the highest crowding group for mortality at 1 and 30 days, but the HR decreased with time and was not statistically significant for mSEAL at 1 and 30 days (Table 8). The analysis was adjusted for age, sex, arrival by ambulance, hospital admission, chief complaint and acuity.

Table 8. Cox proportional hazard ratio for all cause mortality at each crowding exposure with crowding < 85th percentile as reference

Exposure	1-day	7-day	30-day
mSEAL			
85-90%	1.13 (0.83 - 1.66)	0.89 (0.5 - 1.04)	0.95 (0.73 - 1.07)
90-95%	0.93 (0.67 - 1.06)	1.01 (0.89 - 1.13)	1.02 (0.95 - 1.12)
>95%	1.06 (0.99 - 1.24)	1.05 (1.02 - 1.17)	1.03 (1 - 1.11)
OR			
85-90%	1.07 (0.75 - 1.51)	1 (0.74 - 1.25)	0.86 (0.52 - 0.89)
90-95%	0.77 (0.26 - 0.76)	0.95 (0.76 - 1.02)	0.95 (0.81 - 0.98)
>95%	1.13 (1.12 - 1.36)	1.08 (1.08 - 1.24)	1.06 (1.06 - 1.18)

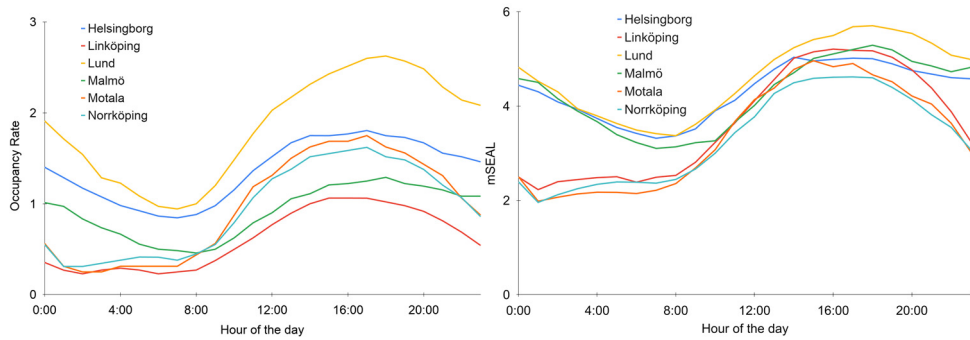**Figure 5: (a) 95 percentile Occupancy Rate for each hour and ED. (b) 95 percentile mSEAL for each hour and ED.**

Crowding measured as mSEAL above the 95th centile for the specific ED and hour of day was associated with increased risk of death when adjusting for possible confounders. This further supports a relationship between crowding and mortality in Sweden, and indicates that mSEAL is able to detect this association.

Discussion

In this thesis we have derived and validated the SEAL model, the first model to measure crowding in Swedish EDs, using staff-assessed workload as the criterion standard. Our results indicate that the SEAL model performs well in EDs of different sizes and in EDs of academic, urban and rural types. Furthermore, we have provided evidence that crowding in Swedish EDs is associated with an increase in all cause mortality at 7 days and that crowding is prevalent in many Swedish EDs. In addition, we have provided insight into the differences between workload and OR as measures of crowding.

The results from paper I indicate a strong correlation between SEAL and staff assessment of crowding, reproducible at five different EDs, spanning rural community EDs with 20000 annual visits to large urban academic EDs with 85000 visits. The correlation ranges from $r^2=0.45$ to 0.64 which is good but not perfect. However, in relation to the complex problem we are trying to measure, we believe this correlation is sufficient to be useful,[103] and comparable with similar data on other metrics for crowding like NEDOCS [64], ICMED [65] and OR [60]. In addition to reproducibility, the modified SEAL (mSEAL) model's ability to predict crowding based on the AuROC scores indicates that it would be usable as a diagnostic tool with both good sensitivity (0.87) and specificity (0.78) for a workload cutoff of 4.5.[90]

Over the past two decades, evidence has been accumulating that ED crowding is a public health problem [27,35,36] and a growing international problem within EM.[104] Accordingly, crowding has been identified as a priority issue for several organisations like the James Lind Alliance and the International Federation for Emergency Medicine.[53,105] In paper II we investigated the prevalence of crowding in Swedish EDs. Although the study included just over half of EDs in Sweden during a limited time period, it showed high OR at 37% of the surveyed EDs. Together with the recent reports by Berg et al.[45] and af Ugglas et al.[41] that found an association between crowding measured as LOS and OR, this suggests that crowding is a prevalent problem in Sweden as well. However, the results are heterogenous and suggest higher OR and boarding rates at academic institutions compared to urban and rural EDs, which is similar to findings in Canada by Rowe et al.[9] According to a recent study by af Ugglas et al., there may be differences between health systems in Sweden as well, since only one out of three included health systems showed a clear association between crowding and mortality.[106] From

an international perspective, the percentage of EDs with high OR was modest, and the number of patients boarding in the ED was markedly low.[7,24,54,107]

The results of paper IV suggest that crowding in Swedish EDs is associated with increased 7-day mortality for our patients with an HR for death at 7 days of 1.08. The HR for mortality decreased at 30 days to 1.03 but was similar to the recent study by af Ugglas et al. that found a HR of 1.08 for 30-day mortality with high ED crowding in 6 hospitals in the Stockholm region in Sweden.[41] Our alternative exposure, an hour- and ED-adjusted OR above the 95:th centile, resulted in a corresponding HR for 7-day mortality of 1.06, indicating validity and reproducibility of our results. Several other studies have shown increased mortality due to ED crowding in specific ED populations,[43,46,49] but our study is one of few to show this in the general ED population.[29,41,42] Death following an ED visit is uncommon in Sweden, with an overall 30-day mortality around 2% and a 7-day mortality between 0.5 and 1%. This low event rate makes the association between crowding and mortality challenging to study, since the effect of crowding is expected to be additive. Patients rarely die directly of crowding but rather of an underlying condition that crowding prevents the provider to detect or treat in a timely fashion.[35] Based on our results we estimate that around 100 deaths per year in Sweden may be attributed to ED crowding. For comparison, a total of 211 people died due to traffic accidents in Sweden in 2019.[108] However, to what extent the deaths due to crowding are preventable requires further study.

Workload as the criterion standard of crowding

We used staff assessment of workload as the criterion standard for ED crowding. There are several reasons for this choice, however, little prior work existed on ED crowding in Sweden to help guide our decisions. First, assessments made by staff have been shown to be a valid, reproducible standard internationally.[34,63–65] The exact wording of the assessments in prior reports have varied with one study using "workload" similar to our method.[63] Secondly, the few other standards that have been used for measuring crowding, like ambulance diversion or LWBS [34,46,62] were deemed unsuitable in a Swedish context. Ambulance diversion is only used in Sweden on very rare occasions,[109] and few EDs systematically track patients LWBS [15,34]. One argument against workload is that its meaning may differ considerably between providers. However, with the mSEAL derivation paper [90] and paper I in this thesis, the mSEAL has now been evaluated against perceived workload in 10 different Swedish EDs at 647 time points with reproducible results, indicating that the measures are generalizable between EDs and providers. Furthermore, in the external validation by Wretborn et al., the cutoffs for OR and NEDOCS that predicted a workload in the highest quartile (>4.5) were 1.2 and 90, respectively.[90] Although not identical with the accepted cutoffs for crowding (1.0 for OR [60] and 100 for NEDOCS [64]), these numbers are close enough to indicate comparability

between the measures and that workload indeed represents crowding [89] as defined elsewhere.

In paper I, we argued that crowding should be rebranded as workload, and we believe that the results of this thesis suggests that workload is another possible metric to estimate crowding, perhaps also outside Sweden, while not replacing crowding. Any imbalance between resources and demand in the input-throughput-model[15] would likely increase workload, and many of the negative effects of crowding have been shown as decreased adherence to treatment guidelines and increased time to treatment.[35] These inabilities are likely the effects of high workload, and it seems reasonable that crowding, without effect on workload, is less relevant both for patients and providers. One potential advantage with a workload-based metric, or any multidimensional model as compared to a specific resource metric like OR, is the ability to identify crowding in different clinical situations. Crude OR would not identify a situation with a few high acuity patients present during the night when staffing is low, even though the mismatch between demand and resources would be equally unbalanced as when OR is high during daytime. However, this theoretical benefit has not translated into a measurable benefit when comparing OR with other multidimensional models, including the mSEAL model.[60,66,90]

Additional value of a combined model compared to single measures

With only two variables in the mSEAL model, its ability to detect crowding situations other than those detected by OR may be limited. Indeed, the results of the external validation of the mSEAL model [90] and the outcomes in paper IV suggests only minor differences between mSEAL and OR. This is likely the result of the strong association between crowding and the number of patients, and also the result of the way the predictive regression modelling used for the SEAL and mSEAL models work. The analysis will exclude any variable that adds little predictive value to the overall performance of the model.[86] Since crowding due to a few but very sick patients is rare in relation to the regular periods of high patient volume, it is likely that our derivation and validation samples included few of these uncommon events. Consequently they contributed little in the selection of predictive variables.

Would the alternative be to use descriptive models without selecting variables to be able to identify these uncommon events? From a data collection standpoint, extracting data from the ED information system, which is used universally in the developed part of the world, is less of a problem now than it used to be. Hence variable optimization is not an argument for selecting the minimum required variables for a model score. However, not selecting predictive variables will mean that there are several variables whose contribution to the model is highly uncertain. There may be some variables which enable the model to perform better in the uncommon, low-resource settings like during nights. But the same variables may also impede the performance of the model during high resource situations with

overall benefit to the model that is questionable. The authors of the ICMED model choose a potential middle way when including several different metrics of crowding in the same model without any regression selection, albeit with a selection before constructing the model.[75] The main difference is that each metric within the ICMED model only contributes towards the extreme values for each metric.[65] The *ED occupancy rate* only adds to the ICMED if there are more patients than beds, 100% and the *ED boarding time* when less than 90% of patients leave the ED within two hours. Instead of filtering variables, this method tries to filter out less relevant values of each variable by using cut-offs.

The determination of cut-offs for each variable then becomes crucial for a model like the ICMED, while the overall cut-off of the model is more important for the mSEAL model. In paper IV we choose a cut-off at the highest five centiles of the mSEAL. With this definition we likely identified the most extreme situations where crowding causes problems. At the same time, with this definition, an ED will always have problematic crowding no matter how good it performs since the cutoff is relative rather than absolute. For the ICMED model, to the best of my understanding, the cut-offs were chosen based on consensus of acceptable quality and risk of harm. When evaluating performance, this may be problematic if the norm, or reality, is so different that the cut-offs are always exceeded. Like e.g. in Beaumont Hospital in Ireland which had a more or less constant ICMED score of seven, no matter what the staff thought.[76] Both the relative cutoffs of the mSEAL model and absolute cut-offs of the variables within the ICMED highlight nuances that are important to understand when measuring crowding. If the aim is to identify situations where crowding causes severe negative effects for our patients, OR or a model like mSEAL with a cut-off relative to normal practice may be useful, provided that the cutoffs are updated as normal practice changes. Absolute cut-offs, like in the ICMED model, may be useful for policy implementation and quality assurance within a defined health care system.

Using the results of this thesis

How should EDs in Sweden measure crowding based on the results of this thesis? For EDs lacking crowding estimation altogether, we would advise starting with OR since this can be calculated easily, even by hand. However, for any crowding score to inform decisions and management, retrospective as well as prospective automatic measuring is important, as shown in paper IV where the definition of crowding was based on historically adjusted averages for each hour. When estimating crowding automatically from EHR data, we would recommend measuring mSEAL as well and to use OR and mSEAL as complements. If the aim is to identify severe negative effects of crowding, it is probably less important which of these two measures is used, but rather how they are interpreted and operationalised, based on the results from paper IV. In the external validation study, a fixed cut-off at an mSEAL score of 4.5 was used to define crowding.[90] However, any such cutoff should be tailored

to a score when crowding impairs patient care or staff wellbeing.[35] Thus, in paper IV we defined crowding as above the 85 th centile for that hour of day and ED, with severe crowding occurring above the 95 th centile, similarly to other international studies.[41,43,84] Our results suggest that the hour-specific absolute cut-offs vary over the day and between EDs, particularly for OR but also for mSEAL (figure 5a, 5b), which supports the concept that there is both local and time variability in crowding.

The variability in time is a logical consequence of the nature of care demand in the ED. There is a common diurnal trend in ED demand with a low number of patients from 00:00 until noon and then steady increase in the afternoon and early evening.[80,91,110] Although there may be slight variations between communities, this trend is likely universal.[111,112] A rationally managed EDs will adapt its capacity through provider and service scheduling to meet this demand.[110,113] Thus, if only measuring demand, it will always be higher at 18:00 than at 08:00. Crowding however, arises when the demand in relation to resources is too high, which means that a crowding measure needs to account for this temporal variation to identify situations of demand-capacity mismatch, not only high demand. It is generally hard to measure capacity, and adjusting for time of the day will do this in a crude fashion. In paper IV we used one hour time periods, compared with af Ugglas et al. that used eight hour shifts.[41] In a previous analysis by Wang et al., periods up to four hours can be used without losing information.[89] If the score is high in relation to the historical data for the time period, indicating deviation from what is expected, crowding is likely.[114] The optimal cut-off for high crowding with mSEAL or OR probably depends on the outcome of interest where more severe outcomes likely occur at higher levels of crowding. Both the results in paper IV and those by af Ugglas et al. suggest that for short-term mortality, this cutoff is somewhere between the 85th and the 95th centile.

In addition to the time of day, it is likely important to adjust for the variability between EDs as well.[114] In paper III and IV we found considerable differences in mSEAL and OR between EDs supporting this. For severe outcomes like mortality, providers probably start to compensate as crowding increases by working faster, prioritizing and limiting efforts to the most necessary care up to a point where they can no longer compensate. Where this turning point appears for a specific crowding measure most likely depends on ED-based resources, like number of treatment beds, nurses etc. In paper III we observed that the number of treatment beds, and therefore OR, vary considerably between Swedish EDs, and that this may affect workload. These differences are reasonable to adjust for when determining the cut-off for crowding in different EDs. This can be done by defining crowding at a relative cut-off for OR (e.g. the top decile) at each ED, rather than an absolute (e.g. 1.0) at all EDs. Indeed, this type of adjustment was made in the studies that found an association between crowding and mortality,[29,41,43,44] including paper IV in this thesis, but it was not made in studies that did not find this association [42,115].

The results of this thesis may be used as a guide to establish cutoffs and measurements of crowding in Swedish EDs. Specifically, paper IV looks at the risk of mortality based on different cutoffs for crowding. However I would like to underline the potential risk of basing cutoffs for crowding on a single outcome of interest. Although mortality is very important for our patients, it is not the only negative effect or crowding that should be targeted. Thus, as described in the introduction, there are several relevant negative effects of crowding on both patient outcomes and providers that may occur above other cut-off levels. Careful consideration should be employed when operationalizing systematic crowding measurements.

Outcomes of interest

Another question is whether the observed increase in mortality, or any negative effect of crowding[35], is preventable. In the conceptual model of crowding the negative effects should decrease when the cause, crowding, decreases. While there are several studies that have investigated different interventions to relieve the ED of crowding the majority of these studies have had a crowding measure as the outcome of interest, like overall LOS, or a very specific measure related to one domain of crowding, like the number of "inappropriate ED attendances" or of "non-emergent ED visits".[36] Additionally, a considerable number of these studies are single center studies from the US.[116] Although several of these studies have shown positive results, it is unclear if the observed crowding effect will carry over to the care of our patients. Many crowding measures are easier to measure than care quality or patient outcomes, but it is important that the measure does not become the end goal of this type of study. It is arguably good to decrease LOS for our patients, but if this comes without an improved quality of care, or with a worsened one, we have likely fulfilled Goodharts law by turning a measure into a target with limited effect for our patients.[117] As outlined by Hansen et al.,[104] studies on interventions targeting crowding should report outcomes across multiple domains of "high quality care" defined by the institute of medicine . An intervention study should thus not only report a single metric, like LOS, but also efficacy through e.g. mortality (possibly via a surrogate measure such as ED and hour-adjusted mSEAL scores as suggested in Paper IV), as well as efficiency through admissions or return visits.

The majority of reports on interventions to reduce crowding focus on persistent long term reductions of crowding which is logical and desirable. However, the potential non-linear relationship of crowding and effects on patient care may render these interventions less effective since the overall crowding may decrease while the extremes still persist. We believe that specific, temporary, directed efforts to intervene on the highest levels of crowding may be cost effective and rational in many health care systems. For instance, a crowding measure like hour- and ED-adjusted mSEAL or OR could be automatically measured in real time with immediate feedback to the ED staff and/or management. At certain predefined

triggers or trends, interventions are initiated to alleviate the ED and avoid the highest levels of crowding. The interventions may differ between hospitals in line with the observed differences in resources observed in paper III, but the cut-offs or triggers for these interventions are likely to be generalisable between EDs, since studies show consistent negative crowding effects at specific cut-offs across multiple centers.[41–44] These triggers and the ability to predict extreme crowding merits more attention and are possible areas of further research. Real time prediction of future crowding has been studied previously with limited utility [62,118]. However, the ability to incorporate community data and our increasing knowledge of predictors of ED demand provide new possibilities to improve crowding prediction.[119]

While the health of our patients and the prevention of morbidity and mortality caused by crowding is our highest priority, the wellbeing of our staff is also important. ED crowding is detrimental to our staff and causes concern, stress and burnout.[40] With the ED being an inherently unpredictable and stressful place, we as providers and managers need to limit any additional stress that adds to this detrimental mixture. Hopefully, this thesis will provide an incentive and the tools to start measuring and working systematically to decrease crowding in the daily ED operations in Sweden. In particular, the observation of the non-linear effects of crowding on patient outcomes may help providers and managers to better understand when crowding is affecting our patients. However, research on provider wellbeing and resilience to crowding is so far largely lacking, and merits more attention. Particularly, researchers should try to understand in what situations crowding becomes a problem for our staff, how different coping strategies help, and how crowding affects providers over time.

Limitations

There are several limitations to the methodology that needs to be accounted for when interpreting the results of this thesis. The mSEAL model was derived as a predictive model which limits the information it provides and the conclusion that may be drawn from the model at any given time. For instance, just because a specific variable is not included in the final model does not mean it does not affect crowding. Consequently, if the crowding phenomenon changes over time, this may alter the model's usability. However, we believe that the risk is fairly small since mSEAL measures the number of patients, their waiting time in the ED and the time to physician; Processes that are fundamental to ED care. Furthermore, mSEAL have only been validated in EDs in Sweden and the generalisability outside Sweden is unknown.

The ability of mSEAL to identify negative effects of crowding is demonstrated in paper IV, and although the effects on the predefined outcome of 7-day mortality

was clear-cut, the CI around the points estimates for 1-day and 30-day mortality were larger. When left-truncating the data, the 7-day mortality point estimate became statistically uncertain as well. We believe that this suggests that our study was underpowered, since the results for our secondary exposure, crowding measured by adjusted OR, showed similarly point estimates as in the larger study by af Ugglas et al.[41] However, our results should preferably be replicated in a larger study as well.

The rationale for adjusting crowding measures by ED is based on the results of paper III, but the results from the mixed linear regression in that study were not statically significant when adjusting for multiple comparisons by the Holm method.[94] Based on the fact that studies finding an association between OR and mortality have accounted for differences between EDs,[41,44] in contrast to studies that have not,[42,115] we believe that study III was underpowered rather than that the results are due to statistical chance. Our rationale for adjusting for time was based on the theoretical model for demand and capacity in the ED, as well as the results of several studies,[41–43,91] including paper IV in this thesis.

Conclusion

In this thesis we have explored the issue of measuring ED crowding with results that provide important groundwork, necessary to systematically measure and interpret crowding in Swedish EDs. Our work primarily focuses on the differences between combined and single measures of crowding, and we suggest staff assessment of workload as the criterion standard for crowding in Sweden.

We provide a novel model to help measure crowding in Swedish EDs, the modified Skåne Emergency Department Assessment of Patient Load (mSEAL). Although the model was modified after the initial derivation, our data suggests that this tool is a valid and reliable measure of crowding in a Swedish setting.

Furthermore, the results of this thesis suggests that crowding is a prevalent phenomenon in Swedish EDs and that situations of high crowding is associated with increased mortality for our patients. Based on these results and on recent evidence provided by others, it seems likely that crowding is associated with increased mortality in Sweden.[41,45,106] We strongly encourage systematic assessment of crowding in EDs, and argue that this should be a cornerstone of quality assurance work in Swedish EDs.[104] This should preferably be done through a mandatory registration in the national quality registry for Swedish emergency departments (SVAR).

While paper I and II primarily provides new information from a Swedish perspective, the results of paper III and IV further builds on previous work regarding confounders when measuring crowding in general.[41,44,91] Specifically, the results highlight the importance of time- and ED related factors, and provide suggestions of how to account for these confounders when measuring crowding.

Populärvetenskaplig sammanfattning

Så länge människan existerat har den haft behov av hjälp och vård i samband med olyckor och sjukdom, även om den medicinska förmågan genom årtusenden varit väldigt varierande. I dagens samhälle står akutmottagningen för kunskapen, resurserna och förmågan att hjälpa människor med många akuta medicinska behov. Välfungerande akutmottagningar har därför en central roll i det moderna samhället. Den enda förbehållet för vård på en akutmottagning är att behovet uppstått akut och kräver behandling eller ytterligare utredning. Detta breda, ospecifika, krav tillsammans med den inneboende svårigheten att förutsäga akuta händelser innebär att behovet som akutmottagningar behöver tillgodose kan variera kraftigt. Samtidigt kräver det moderna samhället en viss förutsägbarhet i planeringen av resurser. Scheman för personal, antalet behandlingsplatser, EKG-apparater etc går inte att anpassa i den hastigheten som behovet förändras på akuten. När resurserna inte motsvarar behovet vid ett givet tillfälle resulterar detta i hög arbetsbelastning, eller crowding, på akutmottagningen.

Hög arbetsbelastning har, ur ett historiskt perspektiv, varit relativt sällsynt på svenska akutmottagningar jämfört med rapporter från Australien och USA. Huruvida detta berott på att det alltid har funnits resurser för att matcha behovet eller för att man inte har rapporterat det är svårt att veta. Det saknas nämligen övergripande statistik för både behov och resurser på svenska akutmottagningar. Socialstyrelsen har gett ut enstaka rapporter de senaste åren som huvudsakligen undersökt belastningen på akutmottagningarna utifrån genomsnittlig total vistelsetid och väntetid till läkare. Även om detta ger en viss indikation på hur våra akutmottagningar fungerar och sannolikt speglar andra aspekter av akutmottagningarnas funktion är det svårt att dra några närmare slutsatser kring belastningen utifrån den här typen av data.

Omkring 2010 började det komma rapporter i media om hög arbetsbelastning på flera av landets akutmottagningar. Under en period avlöste dessa varandra och det blev också ett antal anmälningar till arbetsmiljöverket från skyddsombud kring arbetsmiljön på dessa akutmottagningar. Samtidigt fanns det få verktyg för att mäta arbetsbelastningen och både nyhetsrapporteringen och verksamheterna var begränsade till personalens vittnesmål. Det var utifrån den här situationen som denna avhandlingen tar avstamp. Syftet var främst att förse personal och akutmottagningar med verktyg för att systematiskt kunna mäta och motarbeta hög arbetsbelastning. Samtidigt som vi ville undersöka utbredningen av hög

arbetsbelastning i Sverige och eventuella negativa effekter av hög arbetsbelastning hos våra patienter.

Vi har angripit dessa frågor genom fyra olika studier. I den första studien tar vi fram en modell för att mäta arbetsbelastning och jämför den med internationella mått på arbetsbelastning. I delstudie II undersöker vi förekomsten av hög arbetsbelastning på akutmottagningar i Sverige. Studie III undersöker vi skillnader i två olika mått på arbetsbelastning och några av orsakerna till hög arbetsbelastning. Slutligen tittar vi på eventuella samband mellan hög belastning och död inom sju dagar hos patienter som vistats på akutmottagningen vid hög arbetsbelastning i studie IV.

Den första studien genomfördes på fem olika akutmottagningar i Skåne. Under tre veckor samlade vi in skattningar av ledningsansvarig sjuksköterska och ledningsläkare vid total 233 tillfällen fördelade på de olika akutmottagningarna. Vi samma tidpunkter samlade vi in data för ett antal olika fördefinierade variabler som mätte olika aspekter av belastningen, från akutmottagningarnas ledningssystem. Genom en linjär regressionsanalys selekterade vi sedan fram fyra variabler som tillsammans korrelerade väldigt bra mot den skattade arbetsbelastning. Dessa variabler mätte antalet patienter, dess vistelsetid på akuten senaste timme, väntetid till läkare och andelen högprioriterade patienter enligt det triagesystem som majoriteten av akutmottagningar i Sverige använder för att bedöma allvarlighetsgraden i patienternas akuta tillstånd. Resultaten från den första insamlingen valideras sedan i en efterföljande insamling på två akutmottagningar i Skåne och bekräftade att vår modell sannolikt kunde mäta arbetsbelastning på ett reproducerbart sätt.

Utbredningen av hög belastning på akutmottagningar i Sverige undersöktes i delstudie II. Vi skickade ut förfrågan om att samla in data på antalet patienter, belastning, personal och behandlingsplatser till alla 72 registrerade akutmottagningar i Sverige. Totalt 37 akutmottagningar skickade in komplett data från samtliga fem tidpunkter (00:00, 06:00, 12:00, 18:00, 23:59) under 25:e April 2018. På 12 av akutmottagningarna (37.5 %), vid totalt 31 tidpunkter (18.2%), var antalet patienter högre än antalet behandlingsplatser vilket är ett internationellt vedertaget mått på belastning. Beläggningen var generellt högre på universitetssjukhusen och de större länssjukhusen jämfört med länsdelssjukhusen. Den skattade arbetsbelastning var hög vid 14 (8.2%) av tidpunkterna.. Slutsatserna begränsas av den korta tidsperiod som insamlingen skedde, men utifrån den relativt breda täckningen över landet bedömer vi att resultaten indikerar att hög belastning är ett problem på flera akutmottagningar i Sverige.

Utifrån resultaten i delstudie II observerade vi två grupperingar av akutmottagningar utifrån beläggning. Det fanns ett antal akutmottagningar men hög beläggning vid samtliga tidpunkter som samtidigt skattade arbetsbelastningen på samma nivå som akutmottagningar med betydligt lägre beläggning. Detta blev startpunkten för delstudie III som tittade närmare på detta samband. När vi studerade antalet

behandlingsplatser, en viktig aspekt av beläggning, var det stora skillnader mellan akutmottagningarna där vissa behövde rotera 2.1 patienter per behandlingsplats och dygn medan ett sjukhus behövde omsätta 9.2 patienter per behandlingsplats och dygn. Medel för samtliga akutmottagningar var 4 patienter per plats och dygn. Denna stora skillnad i antalet behandlingsplatser i relation till antalet besök per dag korrelerade starkt till beläggningen, akutmottagningar med få behandlingsplatser att generellt betydligt högre beläggning. När vi justerat för antal sjuksköterskor, läkare, sjukhustyp, beläggning och tidpunkt på dygnet indikerade fortfarande våra resultat att skillnaderna i omsättning påverkade den skattade arbetsbelastningen, även om resultaten inte kunde säkerställas statistiskt. Utifrån våra resultat bör man ta hänsyn till skillnader i behandlingsplatser när man jämför belastningen mellan sjukhus, i synnerhet mätt som beläggningsgrad.

I den sista studien undersökte vi sambandet mellan hög belastning, mätt enligt vår modell från studie I, och dödsfall inom sju dagar hos patienter som vårdats på någon av de akutmottagningar som ingick i studien. Totalt inkluderades ca 170 000 besök av 132 000 patienter från tre akutmottagningar i Region Östergötland och tre akutmottagningar i Skåne under första halvåret 2017. Vi undersökte sambandet med Cox Regressionsmodell, justerat för tidpunkt, akutmottagning, ålder, kön, sjukhusinläggning, sökorsak och medicinsk allvarlighetsgrad. Våra resultat indikerar en statistisk säkerställd ökad risk för död inom 7 dagar om patienten kom till akutmottagningen vid en tidpunkt med mycket hög belastning. Det fanns även en signal för ökad risk för död vid 1 dag och 30 dagar efter akutbesöket även som dessa resultat inte kunde säkerställas statistiskt. Hög belastning har associerats med ökad risk för död i andra studier och våra resultat bekräftar dessa och indikerar att vår modell har möjlighet att identifiera när dessa situationer uppstår.

Sammanfattningsvis har vi i denna avhandling tagit fram ett förslag till modell för att mäta arbetsbelastning på svenska akutmottagningar. Modellen förefaller vara reproducerbar över flera olika typer av akutmottagningar i flera regioner i Sverige och visa samstämmiga resultat jämfört med internationella mått på belastning. Vidare indikerar resultaten från avhandlingen att hög arbetsbelastning är ett problem på flera akutmottagningar runt om i Sverige. Utifrån delstudie IV förefaller hög arbetsbelastning också vara förenat med ökad risk för allvarliga negativa konsekvenser för våra patienter, i form av ökad risk för död inom sju dagar.

Baserat på dessa resultat rekommenderar vi att man skall mäta och arbeta aktivt för att motverka hög arbetsbelastning som en del av det systematiska kvalitetsarbetet på akutmottagningar i Sverige. T.ex. genom att man kontinuerligt och automatiskt rapporterar data till det svenska akutsjukvårdsregistret (SVAR) och regelbundet mäta och agerar på hög arbetsbelastning på sin akutmottagning. Denna avhandling lägger grunden för denna typ av arbete genom om ta fram ett mått på arbetsbelastning i delarbete I och även validera ytterligare ett mått, beläggningsgrad, för mätning av hög belastning.

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Emergency Department Crowding

Jens Wretborn finished medical school at Lund University in 2014. After completing an internship in Eksjö he moved to Linköping where he is currently completing his residency in Emergency Medicine. In parallel with the residency he started his PhD studies in 2017, building on the master thesis that he did under the supervision of Professor Ulf Ekelund at Skåne University Hospital in Lund.

In this thesis Wretborn et al. investigates the issue of demand and resource mismatch in the Emergency Department (ED), known as crowding. Crowding has become an increasingly common problem in many countries around the world and during the last decade concerns have been raised as to the state of emergency medicine in Sweden. There is no validated measure for crowding in Sweden and the extent of the problem is unknown. Despite a longstanding tradition of large comprehensive registries in Sweden, systematic evaluation of ED operations on a national level is lacking. This thesis aimed to supply a base for continued crowding research in Sweden.

The work is a synthesis of four papers with different perspectives on crowding. In the first paper we derive and validate a model to measure crowding based on staff workload. Paper II investigates crowding on a national level by measuring crowding at 50% of Swedish EDs during 24 hours. The prevalence of crowding is assessed by multiple measures and compared between EDs. Paper III builds on the results from the previous paper and further explores some of the differentiating properties of these measures when comparing different EDs. Finally, the forth paper uses the model derived from the first paper to assess whether crowding is associated with negative effects for patients in the ED.