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Contextual design requirements for decision-support tools involved in weaning patients from mechanical ventilation in intensive care units

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ABSTRACT

Weaning patients from ventilation in intensive care units (ICU) is a complex task. There is a growing desire to build decision-support tools to help clinicians during this process, especially those employing Artificial Intelligence (AI). However, tools built for this purpose should fit within and ideally improve the current work environment, to ensure they can successfully integrate into clinical practice. To do so, it is important to identify areas where decision-support tools may aid clinicians, and associated design requirements for such tools. This study analysed the work context surrounding the weaning process from mechanical ventilation in ICU environments, via cognitive task and work domain analyses. In doing so, both what cognitive processes clinicians perform during weaning, and the constraints and affordances of the work environment itself, were described. This study found a number of weaning process tasks where decision-support tools may prove beneficial, and from these a set of contextual design requirements were created. This work benefits researchers interested in creating human-centred decision-support tools for mechanical ventilation that are sensitive to the wider work system.

1. Introduction

Within Intensive Care Units (ICUs), patients are frequently mechanically ventilated via an endotracheal tube. Ventilation replaces or assists a patient's ability to breathe, and is required by around 40% of ICU patients (Wunsch et al., 2013). However, not only is this a costly procedure (Marti et al., 2016), the time taken to wean patients from mechanical ventilation is extensive. Indeed, a significant proportion of time spent in ICU is occupied by the weaning process (Chockalingam, 2015).

Furthermore, the process of weaning is itself complex. There are numerous steps involved to move a patient from fully supported mechanical ventilation to spontaneously breathing on their own. One critical step is extubation, where the endotracheal tube is removed. The readiness for extubation can be difficult to predict, and the timing is important to maximise patient outcomes. If a patient is extubated too early the procedure can fail, which happens in 10-20% of planned extubations (Thille et al., 2013a). This results in re-intubation, which can lead to severe patient discomfort, longer ICU stays, and an increased risk of mortality (Thille et al., 2013b; Krinsley et al., 2012). Conversely, patients extubated too late may experience adverse outcomes such as ventilator associated pneumonia and muscle weakness (Bigatello et al., 2007). It is therefore important for clinicians to recognise the right time to extubate patients.

Due to the complexity of the weaning process, there has long been an interest in designing tools to aid clinical decision-making (Rudowski et al., 1996). So called decision-support tools typically employ machine learning to predict outcomes that may aid clinicians during the weaning process. Currently designed tools include the ability to predict weaning difficulty (Hsieh et al., 2019), successful ventilator mode shifting (Cheng et al., 2022), and extubation readiness (Jia et al. (2021); see Ossai and Wickramasinghe (2021) for an overview). These tools aim to be used alongside clinician judgement when making decisions, and in turn improve patient outcomes.

Some decision-support tools have progressed to initial user testing and deployment in clinical settings. For example, Tsai et al. (2022) developed an AI dashboard to predict real-time adverse prognosis of emergency department patients. The risk of eight diseases was displayed, and clinicians could interact with the tool by changing a patient's features to see how this may affect their risk. After a month's usage, users reported the tool was easy to use and useful to their work. There was also evidence using the tool helped improve patient outcomes.

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However, despite advances in these technologies, overall few have been implemented or maintained in clinical practice (Elwyn et al., 2013). One reason is a lack of consideration for the Human-Computer Interaction (HCI) elements of medical tasks, which prevent tools from fitting within existing work practices (Yang et al., 2019). Consequently, such tools have not adopted a human/user-centred design approach (Gulliksen et al., 2003), meaning they do not consider user needs or work practices. To overcome this, many papers suggesting design requirements for decision-support tools note a need for human-centred design principles; for example, the need to understand the context that tools will be involved in (e.g., Miller (2019); Chromik and Butz (2021); Laato et al. (2022)). A similar principle states the need to identify where a tool is needed early in development, to ensure a suggested change makes sense for the existing system (Gulliksen et al., 2003). Therefore, to design decision-support tools for aiding the weaning process of ICU patients, there is a need to understand the work context to identify areas where tools could provide a needed benefit.

The aim of this study was consequently to understand the ICU work context, and use these findings to create contextual design requirements for decision-support tools for weaning ICU patients from mechanical ventilation. The use of the word contextual denotes that, rather than creating general design requirements for decision-support tools, the current work aims to generate requirements specifically relating to the context of weaning ICU patients from mechanical ventilation. Of specific interest was understanding what decision-making processes are involved during weaning that a decision-support tool could subsequently aid with, and what constraints of the work system exist that may affect the implementation of such tools. To do so, a combination of established methods from human factors research were applied to understand the current work system involved in ICU weaning. These took the form of a Cognitive Task Analysis (CTA) of the decision-making undertaken during the weaning process, and a Work Domain Analysis (WDA) of the constraints that make up the work environment. From these it was possible to identify areas where the weaning process could benefit from the introduction of decision-support tools, and the contextual design requirements such tools would need to meet. The aims of this study were consequently as follows:

1. What decision-making is involved in the weaning process?
2. What are the constraints of the weaning process in ICUs?
3. What contextual design requirements can be gained from these analyses?

2. Relevant literature

As the weaning process is complex, a number of studies have designed decision-support tools to aid in this process. A main focus has been on proving the technology underlying such tools is viable, and able to predict useful metrics a clinician could use. For example, Jia et al. (2021) designed an extubation readiness tool which was also explainable, so that clinicians could understand how the tool works and so use it when deciding when patients should be extubated. Hsieh et al. (2019) similarly designed a tool that could predict weaning difficulty of patients, which clinicians could use to predict which patients may require further assistance. Therefore, if these tools could be successfully implemented into their work environment, they could provide benefits for clinicians.

Consequently, existing tools for the weaning process have considered user needs, in that such tools should be explainable to the clinician. This takes the viewpoint of user/human-centred design, where tools are created to bring human benefits (Gulliksen et al., 2003). However, despite an acknowledgement of the human-centred design process, these designs have not yet considered a key concern of *how* they will be implemented in practice, such as how they will be used by clinicians and when. This is because the context of the weaning process has not been fully explored, which would identify areas where tools would be most beneficial. Even tools that have been successfully deployed into clinical settings have struggled to remain in service long term. Elwyn et al. (2013) conducted a literature review on how many patient decision support intervention tools (DESIs) were successfully implemented into clinical practice. Out of 17 studies, only four achieved the level of ‘change’ (where the DESI has been adopted into practice) and none achieved ‘maintenance’ (sustained use in routine practice). Understanding the context is therefore a necessary next step for decision-support tools, as requirements for how they should be designed must be considered. Fortunately, there is an extensive literature on human-centred design requirements for decision-support tools to draw upon.

Previous research outlining design requirements for human-centred decision-support tools has frequently noted the need to understand the work context. For example, Miller (2019) states the context surrounding where an explanation for a decision-support tool is given should be considered, as well as why an explanation is being presented. Similarly, Chromik and Butz (2021) states decision-support tools should be designed to be sensitive to the context they are designed for, such as by offering functionalities that allow explanations to be adjusted on a contextual basis. These papers are useful to guide the general design of decision-support tools, but they are intended to outline general design requirements for decision-support tools rather than those for a specific context. To account for this, previous work typically states more specific requirements should also be created by analysing and understanding the work context. However, how to gain the necessary information to make contextual design requirements is not well defined or explained. To understand a work context, it is therefore important to take an interdisciplinary approach, and use techniques designed to model complex socio-technical systems. One such field is human factors.

The field of human factors has long explored how to model complex work environments, to identify current practices as well as areas for improvement. Previous work has also specifically considered how to analyse and model elements of the ICU environment, which could identify areas where decision-support tools can benefit the system. For example, St-Maurice and Burns (2017) looked at how patient treatment was related to their medical records. In doing so, the constraints of the current system were observed, allowing suggestions for where interface design improvements could be made to help the work system function. Similarly, Ashoori et al. (2014) wished to understand healthcare team interactions in a birthing unit, to identify the decision-making processes that happen as part of teamwork.

These papers used established methods from human factors for modelling complex socio-technical systems, specifically Cognitive Work Analysis (CWA; Vicente (1999)) and its sub-analysis Work Domain Analysis (WDA; Bisantz and Mazaeva (2016)). CWA aims to analyse, design, and evaluate complex socio-technical systems, and has been applied to a variety of domains. It consists of five phases, where the first stage is a WDA. WDA identifies the current constraints present within a work system by describing the system’s purpose independently of the specific events that occur within it (Bisantz and Mazaeva, 2016). This allows a representation of the work environment to be created, by detailing the physical resources and constraints present within the system which shape the tasks and strategies actors can employ to satisfy the system’s purpose/goals. WDA can be applied in isolation to understand the complexity of a system, as well as identify the potential impact of introducing a change. For example, Austin et al. (2022) used a WDA to understand the constraints on everyday clinical practice in emergency departments.

Other uses of established methods include Cognitive Task Analysis (CTA; Clark et al. (2008)), which focuses on the mental processes involved in performing a task, including the knowledge required to perform it (Clark et al., 2008). This establishes what specific steps make up a task, and the types of cognition that underpin it. For example, Fackler et al. (2009) performed a CTA to understand the types of cognitive activity that critical care physicians undertake, to identify implications for redesigning their workflow.

Overall, current approaches to understand the ICU environment can help identify how the current system operates, which can identify what changes could be made to improve the work system. However, there are limitations when applying previous research to decision-support tools. The work modelling ICU environments via WDAs is done to describe how the overall ICU environment functions, but does not inform in detail how the weaning process is integrated within it. This makes it difficult to understand the specific constraints that may arise when introducing a decision-support tool to the system. The work described above, which models weaning process decision-making via CTAs, has similarly been descriptive, and does not consider how this information can be used to inform design requirements for decision-support tools. Therefore, whilst there is work understanding the work context around the weaning process, it has not yet been sufficiently combined and applied to how the findings can aid in the design of decision-support tools.

Combining the analyses used in the field of human factors to the design of decision-support tools can identify areas where decision-support tools could benefit the weaning process. It would also help create contextual design requirements that researchers interested in creating decision-support tools for ICU weaning can use during development. This will consequently increase the chances tools will be practically useful and adopted into real ICU settings, as the existing constraints of the system are better understood.

3. Method

3.1. The chosen context

As the current work aims to create contextual design requirements for weaning ICU patients from mechanical ventilation, it is important to first specify the specifics of this context. The chosen context was ICUs located in the UK's NHS, particularly those in England. This was due to the relevant expertise and knowledge of the research team, which allowed for opportunity sampling when collecting information about this setting. Whilst a variety of ICU staff are involved in the weaning process, the focus of this work was on consultants, as they are heavily involved in making decisions relating to a patient's weaning progress in the UK. Consequently, they are likely to be the main user group for a decision-support tool introduced into this context, meaning their current workflow and needs require analysis.

Given this context, the results are therefore mainly applicable to the UK's NHS setting for ICU patient weaning, and the needs and work practices of consultants. The generalisability of findings outside of this context is limited, and whilst findings were compared to the international literature to identify any important differences, caution should be taken if applying findings outside of the UK context. To aid in the clarity of this distinction, findings likely specific to the UK context are highlighted throughout the results section.

3.2. Research design

This study consisted of two types of analyses: a Work Domain Analysis (WDA), the first phase of a Cognitive Work Analyis (CWA; Vicente (1999)), and a Cognitive Task Analysis (CTA; Clark et al. (2008)). The combination of WDA and CTA was used to identify the current constraints and opportunities afforded by the work environment, as well as insights into what cognitive processes occur that allow clinicians to perform such tasks. The findings were then used to identify where a decision-support tool may bring the most benefit, and devise contextual design requirements.

When considering a work system, it is important to define the boundary of what constitutes the work environment, to ensure the WDA and CTA provide practically useful findings for the given application. As this study focuses on how clinicians wean patients from mechanical ventilation in the ICU environment, only activities related to patient weaning were considered. Therefore, the analysis considered the work system's functions and the tasks that make up the process of weaning patients, i.e., from the resolution of the initial condition they were administered for to the time of being fully extubated from respiratory support.

The **WDA** was used to identify constraints that may affect the introduction of a new decision-support tool. Rather than model the entire ICU work context (as has been done previously e.g., St-Maurice and Burns (2017)), the goal of this work was to create contextual design requirements for decision-support tools in ICU weaning. Consequently, only the first stage of CWA was conducted, to identify what steps are taken as part of weaning, and what constraints and affordances affect these steps. Other stages of a CWA — i.e. a control task analysis (ConTA), a strategies analysis, a social organisation and cooperation analysis (SOCA), and worker competencies analysis (WCA) — were not conducted. The reasons for this are as follows. First, we conducted a Cognitive Task Analysis (CTA) instead of ConTA, as the types of data collected in this study were not suitable to support the creation of a model such as a decision ladder (Rasmussen and Jensen, 1974). For the interest of this study, we did not need to fully understand the cognitive processes of the clinicians in the ICU, as the aim was to understand the general process of weaning in order to support the identification of areas where decision-support tools may provide the most benefit. Furthermore, there are benefits to employing 'many models thinking' when understanding complex socio-technical systems (in this case, using the combination of a WDA and CTA) as the findings across different methods can be combined to generate useful insights that help make better interventions (Salmon and Read, 2019). Second, in terms of strategies analysis, these were only explored insofar as outlining what patient information and measurements clinicians base their decisions from, to identify what information would be required by a decision-making tool. This is because currently there is little agreement on the protocols or strategies for weaning patients in ICUs (Pham et al., 2023), and it is not the aim of this study to address this issue. Third, In terms of SOCA, it was also not the aim of this study to outline every possible social interaction that may occur during weaning, as these are likely unique to a specific ICU rather than reflective of UK ICU weaning overall. Instead, it was only necessary to identify the typical types of information sources used in weaning decision-making and thus would be needed by a decision-support tool. Fourth, in terms of WCA, it was not the aim of the study to understand what competencies the staff involved in weaning possess, but rather what competencies should a decision-making tool introduced into this work domain possess. These could instead be derived by producing contextual design requirements based on the findings from WDA and CTA, therefore this stage was not required.

Therefore, performing a WDA in isolation was able to represent the work environment where weaning takes place, to identify constraints and opportunities imposed/afforded that may affect the design of decision-support tools. This represents a first step in understanding how clinicians perform the weaning process.

Within WDA, there are several methods available depending on the focus of a project. For this study, the goal was to understand the weaning process and its related tasks performed by ICU clinicians, to inform how decision-support tools could aid this process. Two analyses were conducted, guided by previous work exploring ICU work systems:

- *Abstraction Hierarchy* following the approach of St-Maurice and Burns (2017), but using the more up to date terminology suggested by Reising (2000). Here, a work system is represented as five levels of abstraction, to explain how the physical objects in a system relate to the functions and overall purpose of the system, whilst identifying the relevant constraints and opportunities at each level (Kilgore et al., 2016). Doing so identifies constraints and opportunities that either cannot be avoided or could suggest places for potential improvement via the introduction of decision-support tools. Whilst WDA typically models an entire system (such as St-Maurice and Burns (2017)), for this study only the environment directly related to the weaning process was considered. This allowed for a smaller, more contained and granular analysis of the weaning process.

- *Information Flow* inspired by Ashoori et al. (2014). This identifies how information is passed between users in a work system, and can also reveal the types of strategies a user might employ when using this information (Vicente, 1999). For this study, it was important to map the flow of information across a clinician's typical daily workflow (i.e., what information is considered when), as well as where this information originates from, due to the inherent multidisciplinary nature of the ICU environment. Outlining these information flows identifies the constraints on when decisions are made, and where information is obtained during the weaning process.

A **CTA** was also conducted, to identify what cognitive processes occur during the weaning process, to indicate points where clinicians may receive the most benefit from the introduction of a decision-support tool. For example, if a decision-support tools aims to reduce the cognitive workload of clinicians, a CTA can help to identify points in the weaning process where there is high cognitive workload. A CTA can also identify the types of knowledge/information a clinician requires at each step, which reveals what information a decision-support tool would need to provide to a clinician and at what times. Similarly to WDA, there are several types of CTA available. Two analyses were conducted:

- *Patient Workflow*: to understand the decisions made during weaning, a typical patient workflow through the weaning process was created based on the approach used in St-Maurice and Burns (2017). This identified what steps a patient progresses through when being weaned from respiratory support, to identify stages where decision-support tools may bring the most benefit to clinicians.
- *Cognitive Workload Classification*: to understand what is involved in each step in the weaning process, in terms of the cognitive elements and associated workload, a task analysis of decision-making steps was performed. Doing so can reveal where in the weaning process a decision-support tool may bring the most benefit. The cognitive task analysis method used in Knisely et al. (2020) was followed, which involved applying Bloom et al. (1956)'s taxonomy of cognitive complexity to the identified cognitive steps, to reveal steps with high workload.

3.3. Data collection & analysis

To perform the analyses, three data sources were used as the primary data; existing academic literature explaining the weaning process, interviews with ICU clinicians, and existing weaning guidance recommended by ICU clinicians.

Firstly, existing literature explaining the weaning process were sourced. The terms “weaning process” AND “mechanical ventilation” were entered into PubMed to find papers published after the year 2000, with an initial sample of 767 papers. Duplicates were removed reducing this to 764. Initially, papers were screened by title. Many studies referred to outcomes for a specific patient group, such as children or the elderly, and so were removed as the goal was to find a description of the weaning process. This left 513 papers. Studies that focused on a specific illness were also removed, such as patients with brain injuries or a terminal illness, leaving 438 papers. Next, studies that analysed the effects of implementing a change to the weaning process were removed, such as randomised control trials, leaving 339 papers. Studies that predicted the outcome or risk of a patient, such as extubation failure, were then removed, leaving 245 papers. Finally, papers focused on a specific element of the weaning process were removed (e.g., the role of blood gases, adherence to protocols, the management of pain, the patient's lived experience), leaving 82 papers, and those considering the weaning process from a specific user's perspective (e.g., neurologists or nurses), leaving 68 papers.

The abstracts of the remaining 68 papers were then assessed to identify papers specifically explaining the weaning process. Papers that did not fit the inclusion criteria used for title screening were removed (e.g., intervention studies, specific patient groups), leaving 31 papers. Papers not written in English or otherwise inaccessible were removed, leaving 21 papers, as well as papers that described differences between available weaning processes, leaving 16 papers. 5 of these papers reported general weaning outcomes; Pham et al. (2023) was chosen to represent these papers as it was the most recent and was an international consensus across 50 countries. This left 12 papers that described the weaning process. However, many only gave general information, such as stating a Spontaneous Breathing Trial is performed or that weaning readiness is assessed, but did not identify or explain what variables are associated with these steps. Further, papers that did provide guidance on variables clinicians consider whilst weaning consistently overlapped. Therefore, the most detailed of these papers were chosen for analysis.

The final literature sample therefore contained five articles: the findings of an 11-member international jury from the International Consensus Conference on Intensive Care Medicine (2005) that provided recommendations for the weaning process (Boles et al., 2007), two clinical reviews on extubation and how extubation decisions are made (Thille et al., 2013b,a), a review on ventilator weaning and Spontaneous Breathing Trials (SBT; Zein et al. (2016)), and an international cohort study on weaning processes (Pham et al., 2023). In doing so, it was possible to analyse the general academic guidance on how weaning is conducted.

To understand the decision-making involved during the weaning process from a clinician's perspective, three interviews with ICU clinicians were conducted using opportunity sampling. Consultants were chosen as the primary sample as UK ICUs are designed to be primarily consultant-led (GPICS, 2022), and so were best placed to describe the weaning process. Whilst a small sample, the general operation of ICU is standardised across the UK, meaning it was possible to extract and describe the general weaning process from the participants. However, it is important to note that the representativeness of our sample is limited to the UK ICU context.

The clinicians were invited to attend an online Zoom meeting, where notes were taken from the discussion around their weaning practices. The interview schedule was co-created by our multidisciplinary research team, which included computer scientists, a HCI researcher, a human factors specialist, and a critical care & anaesthesia ICU consultant with software development experience. The focus of the questions was on the practical elements involved in the weaning process, such as how consultants approached the weaning process, the information they used to make their decisions, and identifying areas where complex decision-making was involved. Alongside this, they were asked for their thoughts on how decision-support tools may aid this process, to understand their needs when introducing a change to their work context. The study was approved by the University of York Physical Sciences Ethics Committee (Ref: Jia20230525) and by the Health Research Authority (Ref: IRAS 332567). The first consultant had 10 years ICU experience, and was also an anaesthetist. The second consultant was an intensive care and respiratory doctor, anaesthetist, and academic fellow. The third participant was a senior intensive care registrar in the last year of training for anaesthetics & intensive care medicine. Each interview began by obtaining informed consent, and lasted one hour.

Finally, publicly available guidance on the weaning process were sourced following suggestions from the interviewed clinicians, to find data they recommended that may not have been found in a typical academic search. This included the role of sedation written by a pulmonary intensivist,[1] an overview of the weaning process written by an

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[1] Retrieved from https://emcrit.org/ibcc/pain on 22/09/2023.

intensivist,[2] the Guidelines for the Provision of Intensive Care Services (GPICS) from the Intensive Care Society,[3] and a randomised clinical trial on the effects of weaning protocols on time to extubation (Perkins et al., 2018). These provided further information to the previously collected literature and interview data.

These three primary data sources were then used in combination to perform the WDAs and CTAs, by extracting information about the tasks and processes involved in the weaning process, the daily work and information flow of clinicians, and the purposes and functions of the work system. In doing so, the tasks that make up the weaning process and the work system that surrounds this process could be understood. After the initial WDA and CTA analyses were complete, the results were discussed within our multidisciplinary research team to provide further clarifications, contextual information, and insights to aid in the write-up of results.

3.3.1. *Reflexivity statement*

Due to the qualitative nature of the work, it is important to consider how the research team may have impacted the analysis. The work was conducted by an interdisciplinary team of computer scientists, a HCI researcher, a human factors specialist, and a practising consultant intensivist/anaesthetist. This allowed for a diverse range of expertise and inputs to help guide the methodology and analysis, which included how AI decision-support tools are developed, how users typically interact with tools, and how UK ICUs operate. However, it is important to consider how this may have impacted data collection and interpretation of results.

Firstly, the approach to finding primary data was influenced by the team makeup. An academic literature review was conducted to find information on the ICU weaning process. Whilst such papers likely have clinical input, they are written primarily by and for an academic audience, so may miss important details about the more practical nature of ICU weaning. To overcome this, literature outside of academia was also sourced on recommendation from the interviewed consultants. A further limitation however is that existing literature is a secondary data source, and does not allow specific questions to be asked about the process. To overcome this interviews with ICU clinicians were conducted to gain first-hand information on the ICU weaning context, and the specifics of what decision-making takes place. By combining these three data sources, and both primary and secondary data, the ICU weaning context could be described using both academic and clinical data, increasing the richness of the dataset.

Secondly, the interview questions, and who was approached to take part in the interview, were influenced by the team. To ensure questions were appropriate for clinicians whilst still aimed at understanding the ICU weaning process, the team discussed the questions together as part of a workshop. From this the final set was devised, where the focus was on how consultants approached weaning and their ideas on best practice. In terms of participant recruitment, we used opportunity sampling using contacts available from the team's practising clinician, which biased the sample towards the UK, NHS ICU setting. This limits the generalisability of the findings to the UK ICU weaning context, and so interview data were paired with international consensus literature to appropriately situate the findings.

Finally, data interpretation involved synthesising the differing viewpoints within our team, which was achieved by presenting findings in a team workshop. This allowed each author to comment on the results and suggest clarifications or improvements, with the aim to keep findings both theoretically and practically useful to a clinical audience.

Overall, the multidisciplinary nature of the team was a benefit to this study, but it also introduced some biases. Whilst steps were taken to mitigate them, the current findings are likely to generalise only to the UK ICU context, and care should be taken if applying the suggested design requirements to other international contexts.

4. Results

4.1. *The weaning process*

This sections overviews what the weaning process is, in the form of a patient workflow diagram, associated information required at each stage, and the CTA breakdown of workload.

4.1.1. *Patient workflow*

Fig. 1 shows the typical steps an ICU patient may take whilst weaning from mechanical ventilation, as described by the interviewed ICU clinicians and relevant literature. It is important to note this is an abstraction of the complex parallel tasks undertaken during weaning, which are unlikely to be captured fully in any one diagram. Indeed, it is still unclear how best to define when the weaning process actually begins and ends (Pham et al., 2023). The boundaries between steps are fuzzy due to the number of parallel processes, both within weaning and as part of other treatments occurring. Further, whilst there is a natural progression through the steps as weaning progresses, a patient's status can deteriorate, which means they move backwards through the diagram to the last viable step where they are stable. However, the present diagram provides an initial starting point to explore the types of tasks that occur during weaning for a 'typical' patient, to isolate areas where decision-support tools may aid clinicians in these tasks.

Table 1 briefly describes each step in this process. Patient weaning has three main stages: extubation preparation, assessment of extubation readiness, and extubation. Within these are 9 steps a patient moves through, though some steps may be repeated depending on the individual improvement in condition, and some may be skipped if a patient is progressing well. For example, when adjusting the ventilator setting, some patients may not respond well and require the setting to be changed back. Only when the ventilator setting can be successfully changed can they move out of the 'adjust ventilator' to 'assess weaning progress' loop, indicated by the bidirectional arrows within the grey box in Fig. 1. Further, some patients show early signs of extubation readiness, and so do not require a Spontaneous Breathing Trial (SBT) before extubation. Each step is now described.

Extubation preparation begins when the patient's initial reason for intubation has been reasonably resolved. At this stage, the patient is fully supported by a ventilator, cannot breathe spontaneously, and is unconscious (i.e., sedated). From here, the patient's **weaning readiness** is assessed, by considering their current condition and the likelihood they will respond positively to a reduction in respiratory support. If the clinician decides the patient is ready, the process of weaning begins. This involves beginning to reduce respiratory support by adjusting the patient's **ventilation** and **sedation** support. The patient is monitored for their response to these adjustments, and their **weaning progress** is routinely assessed. At this point, further adjustments to ventilator and sedation settings may be required – either because the patient is responding well meaning support can be further reduced, or because they are not and so require more support/a longer period of time at the current setting.

Constant monitoring is important at this stage, as a patient's condition can easily deteriorate. Selecting the correct levels of sedation to wake a patient is not always straightforward, and there may be other concerns, such as the underlying condition deteriorating, a temporary obstruction forming such as a mucous plug, or the patient simply being too tired from overworking their respiratory system. However, it is still important to progress a patient to the next step. Progressing too slowly can also be detrimental to their health; a patient may develop a ventilator-associated pneumonia or respiratory muscle deterioration/weakness if left on mechanical support for too long, which is

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[2] Retrieved from https://litfl.com/weaning-from-mechanical-ventilation/ on 22/09/2023.

[3] Retrieved from www.ficm.ac.uk/standardssafetyguidelinesstandards/guidelines-for-the-provision-of-intensive-care-services on 22/09/2023.

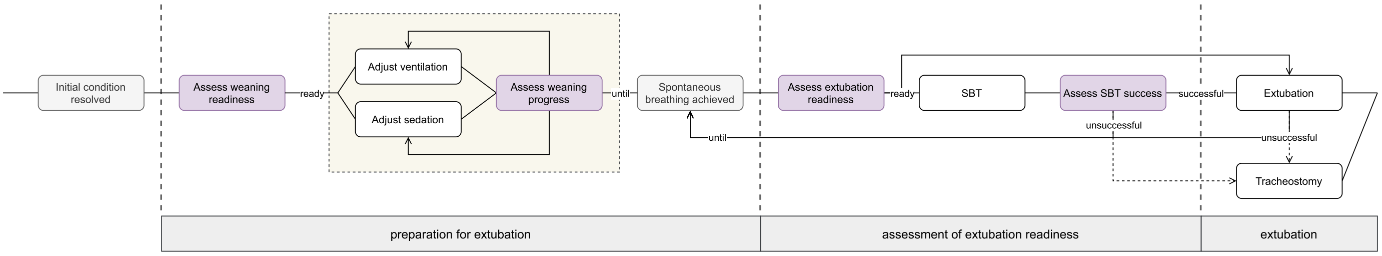

Fig. 1. An abstraction of the weaning process the typical patient goes through. Purple boxes indicate assessment steps, and grey boxes indicate patient statuses (for interpretation of the colours in the figure, the reader is referred to the web version of this article.)

Table 1
An overview of the steps taken during the weaning process.

Stage	Step	Description	Type
	Initial condition resolved	The initial reason the patient was admitted to ICU has been sufficiently resolved	Status
Extubation preparation	Assess weaning readiness	The patient is assessed for their readiness to be removed from respiratory support	Assessment
	Adjust ventilation	The patient's ventilation support is reduced to increase their ability to breathe spontaneously	Task
	Adjust sedation	The patient's sedation levels are reduced to increase their consciousness	Task
	Assess weaning progress	The stability of the patient as the new levels of ventilator support and sedation are assessed	Assessment
	Spontaneous breathing achieved	The patient can breathe with minimal/no respiratory support	Status
Extubation readiness	Assess extubation readiness	The patient is assessed for their readiness to be removed from respiratory support	Assessment
	SBT	A spontaneous breathing trial is performed	Task
	Assess SBT success	The ability of the patient to breathe without respiratory support is assessed	Assessment
Extubation	Extubation OR	The endotracheal tube is removed from the patient	Task
	Tracheostomy	A tracheostomy is performed	Task

Table 2
The variables that may be considered when deciding on extubation readiness. SaO_2 = arterial oxygen saturation, FIO_2 = inspiratory oxygen fraction, PaO_2 = arterial oxygen tension, PEEP = positive end-expiratory pressure, 1 mmHg = 0.133 kPa.

Type of criteria	Considerations when assessing readiness for extubation
Clinical & Context assessment	Resolution of the reason the patient was intubated
	Adequate cough
	Cooperative & pain free
	Absence of excessive tracheobronchial secretion
	Staffing levels and time of day is optimal
Objective measurements	Clinical stability
	- Stable cardiovascular status
	- Heart rate $\leq$ 140 beats·min
	- Systolic blood pressure 90 - 160 mmHg
	- No/minimal vasopressors ($<$0.05 μg/kg/minute noradrenaline)
	- Stable metabolic status
	- Adequate mentation
	- No sedation/adequate mentation on sedation over the last 24 hours
	- Glasgow Coma Scale >8
	Adequate oxygenation
	- $SaO_2 > 90\%$ on $\leq FIO_2$ 0.4 (or $PaO_2:FIO_2$ ratio >200 mmHg)
	- PEEP <10 cmH_2O
	Adequate pulmonary function
	- Respiratory rate $\leq$ 35 breaths·min
	- Tidal volume >5 $mL{\cdot}kg^{-1}$
	- Rapid Shallow Breathing Index (RSBI) <105 breaths·min
	- No significant respiratory acidosis (pH $\geq$ 7.30)

a primary reason why early extubation is important. This loop of assessing the patient and adjusting the ventilator and sedation settings continues until **spontaneous breathing** is achieved, defined here as when the total respiratory rate is higher than that of the ventilator setting, and as such the patient is triggering the ventilator (Pham et al., 2023). Over 90% of patients will show signs of spontaneous breathing a median of 3 days after intubation (Pham et al., 2023). Initial spontaneous breathing may be accompanied by a high pressure support from the ventilator, which over time is adjusted to low pressure support as the patient gradually takes on more of the work of breathing.

Extubation readiness assessment begins when the patient has achieved spontaneous breathing with low assistance pressure and low Positive End Expiratory Pressure (PEEP). The clinician then assesses whether the patient is ready for **extubation**. Similarly to assessing the weaning progress, the clinician considers the patient's current condition as well as their trajectory over the course of weaning. The types of information clinicians may consider is shown in Table 2, adapted from Boles et al. (2007) and Perkins et al. (2018), and combined with input from the interviewed clinicians.

If extubation seems likely to be successful, the patient will commonly undergo a **Spontaneous Breathing Trial** (SBT), where they are temporarily removed from respiratory support or placed on an established minimum respiratory support level. In some cases, it is not always necessary to conduct a formal SBT if the clinician believes the patient

Table 3
Success criteria for an SBT, where PaO_2 = arterial oxygen tension, FIO_2 = inspiratory oxygen fraction, SaO_2 = arterial oxygen saturation, $PaCO_2$ = arterial carbon dioxide tension, 1 mmHg = 0.133 kPa.

Type of criteria	Success criteria for Spontaneous Breathing Trial
Clinical assessment and subjective indices	No agitation and anxiety No depressed mental status No sweating/clamminess No diaphoresis No cyanosis No evidence of increasing respitory effort - No increased accessory muscle activity - No facial signs of distress - No dyspnoea
Objective measurements	Adequate oxygenation - $PaO_2 \geq 60$ mmHg on $FIO_2 \leq 0.4$ or $SaO_2 > 90\%$ - $PaCO_2 < 50$ mmHg or an increase in $PaCO_2 < 8$ mmHg - pH > 7.32 or a decrease in pH ≤ 0.07 pH units Adequate pulmonary function - Rapid Shallow Breathing Index (RSBI) <105 breaths·min - Respiratory frequency <35 breaths·min or increased by ≤ 50% - Cardiac frequency <140 beats·min or variability ≤ 20% - Systolic blood pressure <180 mmHg or >90 mmHg or change ≤ 20% - No cardiac arrhythmias

Table 4
Success criteria for extubation within 48 hours, where SaO_2 = arterial oxygen saturation, PaO_2 = arterial oxygen tension, FIO_2 = inspiratory oxygen fraction, $PaCO_2$ = arterial carbon dioxide tension, 1 mmHg = 0.133 kPa.

Type of criteria	Success criteria for extubation
Clinical assessment & subjective indices	No clinical signs of respiratory muscle fatigue or increased respiratory effort
Objective measurements	Respiratory frequency <25 breaths·min for 2 h Cardiac frequency <140 beats·min or sustained increase/decrease of <20% $SaO_2 > 90\%$; $PaO_2 > 80$ mmHg on $FIO_2 \leq 0.5$ No hypercapnia ($PaCO_2 < 45$ mmHg or ≤ 20% from pre-extubation), pH >7.33 No cardiac arrhythmias

is already ready for extubation. For example, patients may show signs considered equivalent to an SBT, such as a low pressure support (e.g., 5cmH_2O PEEP with 10cmH_2O support). How the patient responds to the SBT is then assessed – if the patient responds well, extubation can occur. If they respond poorly, they will likely be put back onto respiratory support, though in some cases extubation can continue successfully with non-invasive support (Perkins et al., 2018). Around 70% of mechanically ventilated patients fall into the simple weaning group (i.e., pass the SBT trial and are successfully extubated on the first attempt, Boles et al. (2007)). However, according to the review of Thille et al. (2013a) nearly 50% of patients did not pass the first SBT, which increased to 70% for patients ventilated for more than 2 days. Therefore, there is a high variance in the trajectory of patients through the weaning process. The success criteria for an SBT are shown in Table 3, adapted from Boles et al. (2007), Perkins et al. (2018), and Zein et al. (2016).

When a patient successfully passes an SBT, they are ready for **extubation**, where the endotracheal tube is removed. Success criteria for extubation are shown in Table 4, adapted from Boles et al. (2007). The patient is monitored for signs of deterioration as they may need re-intubating. Re-intubation is considered extubation failure if it occurs within a defined period, usually 48 hours (Boles et al., 2007). This may happen despite a patient meeting all extubation readiness criteria and successfully passing an SBT; Thille et al. (2013a) reported this can occur in 10-20% of planned extubation cases. Failed extubation and subsequent re-intubation should be avoided, as this is associated with higher mortality (Thille et al., 2013b). It is therefore important that a patient is highly likely to breathe on their own following extubation before being removed from ventilation. In the case of repeated extubation failures, a **tracheostomy** may be considered.

4.1.2. Cognitive workload classification

A cognitive task analysis was performed to break down what activities occur at each step in the weaning process, to identify the types of work and workload expected. This followed the cognitive task analysis method of Knisely et al. (2020), which applied the taxonomy of cognitive process of Bloom et al. (1956) to the identified tasks to reveal where the cognitive complexity occurs in the weaning process. Table 5 shows the findings of the CTA. To illustrate the insights gained from such an analysis, the steps involved in the extubation readiness stage are explained below, as this stage involves a high volume of cognitive tasks.

In the **assess extubation readiness** step, the clinician must decide whether a patient is ready for exubation. The clinician, typically the consultant, considers a variety of data sources, including the Electronic Healthcare Record (EHR) data of the patient, the settings of the ventilator, the settings of the infusion pump, observations of the patient, observations from the bedside nurse, and observations of the current ICU environment. Each data source requires two types of cognitive knowledge: recalling what the data looked like over the course of weaning (typically the last 48 hours), and recalling what the data range is expected to look like for a patient ready to begin extubation. For example, a clinician may consider how long the patient has been relatively stable in their cardiovascular status, as whilst it may currently be stable (i.e., the patient requires no or minimal vasopressors), in the previous 48 hours there may have been complications that imply the patient may not respond well to extubation at this time. Therefore, the clinician considers what the current cardiovascular status is, whilst recalling the previous status and expected ranges for the patient.

As can be seen, a lot of data originates from observations, which involves clinicians deciding how a patient ‘looks’ such as how responsive they are when spoken to. Whilst this can be measured via specific instruments such as the Glasgow coma scale (which should be at least

Table 5
A CTA of the extubation readiness stage of the weaning process, indicating the types of cognitive work present.

Task	Cognitive process	Taxonomy classification	Cognitive task
Assess extubation readiness	Analyse EHR data	Knowledge	- Recall previous data - Recall typical values
		Comprehension	- Classify data against expected ranges
	Analyse ventilator	Knowledge	- Recall previous settings - Recall typical values
		Comprehension	- Analyse time on ventilation - Classify setting against expected setting
	Analyse infusion pump	Knowledge	- Recall previous settings - Recall typical values
		Comprehension	- Analyse time on sedation - Classify setting against expected setting
	Analyse patient	Knowledge	- Recall previous patient condition - Recall typical patient condition
		Comprehension	- Classify patient against expected condition
	Communicate with bedside nurse	Knowledge	- Recall patient information
		Comprehension	- Discuss observations
	Analyse current ICU environment	Knowledge	- Observe current environment - Recall typical busyness levels
		Comprehension	- Classify environment as busy or not busy
	Synthesise observations	Application	- Compare current observations against expected values
		Analysis	- Compare and contrast all available observations
		Synthesis	- Combine observations together
	Decide on extubation	Application	- Decide whether to begin extubation based on current observations
		Evaluation	- Evaluate if the decision is correct
SBT	Change the ventilator setting	Knowledge	- Recall how to change the ventilator
		Application	- Interact with the ventilator
Assess SBT success	Analyse EHR data	Knowledge	- Recall previous data - Recall typical values
		Comprehension	- Classify data against expected ranges
	Analyse patient	Knowledge	- Recall previous patient condition - Recall typical patient condition
		Comprehension	- Classify patient against expected condition
	Synthesise observations	Application	- Compare current observations against expected values
		Analysis	- Compare and contrast all available observations
		Synthesis	- Combine observations together
	Decide the outcome	Application	- Decide if SBT was successful based on current observations
		Evaluation	- Evaluate if the decision is correct

8 before extubation can begin), or the Richmond Agitation/Sedation (RASS), the clinician will also apply ‘common sense’ as to how responsive and well the patient appears. Collecting observations also involves asking others for their opinions. For example, consultants can ask the respiratory physiotherapists for their observations, as they are involved in clearing secretions from unconscious patients and interact with conscious patients who are able to expel secretion from the lungs on their own. They can also ask the bedside nurse about a conscious patient’s agitation/mental status.

Having both sets of knowledge allows comprehension to occur, where the clinician can decide if the current data falls within the expected range, whilst also considering the trajectory of the patient. Once all data sources have been collected, it is possible to synthesise observations, by considering how each data source fits within its expected value range. Whilst some data are easy to interpret as indicative of patient readiness, such as optimum requirements for ventilator pressure support, other data require more subjective consideration, such as neurological status. From here, the clinician can decide if the current scenario reflects what they expect of a patient ready for extubation. This process is complemented by the clinician comparing all available observations against one another to detect conflicts/abnormalities, which relies on their professional knowledge and experience.

At this stage, the clinician can engage in a discussion within the multidisciplinary team about the patient, with a heavy reliance on the input from the physiotherapists and bedside nurses. This is especially helpful to provide a full picture of a patient’s current state, as well as when handling complex cases or conflicting data. For example, if a patient has a high volume of secretions or a poor cough, identified by the physiotherapist, then extubation may be initially successful but rapidly fail as the secretions build up. The clinician may also use the pressure numbers from the ventilator, the results from a Rapid Shallow Breathing Index (RSBI), or the calculation of Vital Capacity (VC), though the use of specific measurements varies between units.

Finally, all observations, classifications, and comparisons are combined to create an overview of the patient’s current state. This involves the cognitive tasks of application, analysis, and synthesis. From here clinicians decide whether the patient should be extubated via the cognitive task of application. The clinician then reflects on this decision to check they believe it is correct, involving the cognitive task of evaluation. However, it is important to note the final decision to extubate or not can vary depending on who is making the decision, and the makeup of the multidisciplinary team working at that time. Extubation readiness is not an assured binary answer, as it is based on the probability of success. Consequently, clinicians vary on their levels of risk tolerance and judgement of how likely a patient is to successfully breathe on their own, which affects what decision is reached for a given patient at a given time.

Once a decision has been made to begin extubating a patient, the next stage in many cases is to initiate a **Spontaneous Breathing Trail (SBT)**, where the patient is tested for their ability to breathe without

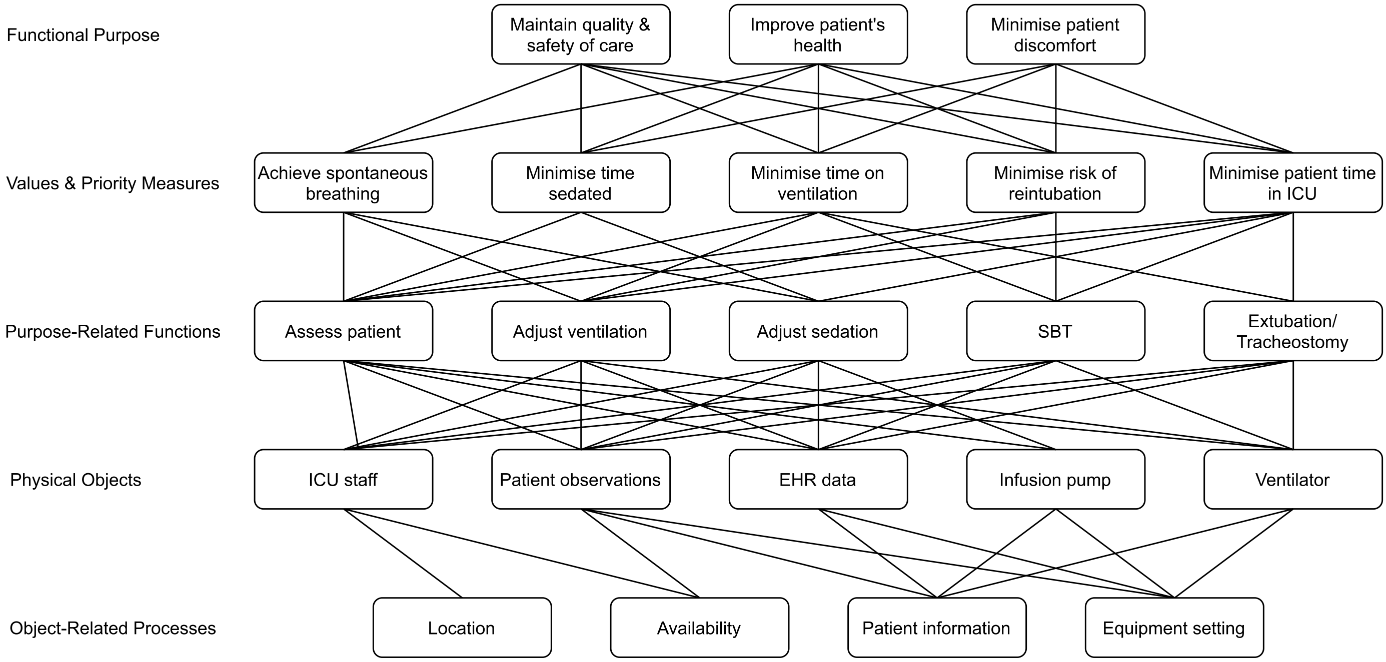

Fig. 2. Abstraction Hierarchy for the weaning process.

respiratory support. As mentioned earlier, a clinician may believe a patient shows signs of extubation readiness equivalent to an SBT, and so opt to move straight to extubation. When an SBT is performed, this involves changing the ventilator settings, which in turn involves the clinician recalling how to operate the equipment and applying this knowledge to interact with it.

Once the SBT trial has been completed, the clinician decides whether it was successful by **assessing SBT success** criteria. This involves observing how the patient is responding, and consulting the EHR data. There are a number of signs that the SBT is not successful, from noted facial signs of distress to cardiac arrythmias. Each observation is considered by the clinician and synthesised together to decide the outcome of the SBT, similarly to how the assessment of extubation readiness is performed. If it is successful, a patient can be extubated. If not, patients can be put back onto respiratory support until they are able to try again. In around 10% of cases (Frutos-Vivar et al., 2005), patients are given a tracheostomy. A common reason for opting for a tracheostomy is if there are repeated SBT failures.

Overall, extubating a patient involves all six types of cognitive process according to Bloom et al. (1956). There are numerous knowledge and comprehension tasks, followed by points where the clinician applies this information to the current setting to make a decision, involving application, analysis, and synthesis tasks. Consequently, the assessment stages are the most cognitively taxing, as they involve both the largest number and variety of cognitive tasks. Therefore, a tool designed to aid in assessment would likely yield benefits in decreasing clinician workload.

4.2. The constraints of the weaning process work system

This section overviews the work context of the weaning process, using an abstraction hierarchy and information flow map. These identify constraints in the weaning process and where information is obtained for decision-making.

4.2.1. Abstraction hierarchy

Fig. 2 shows the abstraction hierarchy created for the weaning process. This figure was created by the following steps. To begin, the patient workflow described in the CTA was used as the Purpose-Related function layer. Using this, along with the information gathered from the clinician interviews and literature, three Functional Purposes of weaning a patient were created. The next step involved connecting the Functional Purposes of weaning to the Purpose-Related Functions, by outlining the Values and Priority Measures. For example, the Values and Priority Measures associated with performing the Purpose-Related Function of 'SBT' are: minimising the risk of reintubation, minimising patient time in ICU, and minimising time on ventilation. In turn, these connect to the Functional Purposes. For example, the 'minimise time sedated' measure is in service to the 'maintain quality & safety of care' and 'improve patient's health' functional purposes of weaning. Following this, the Physical Objects associated with the Purpose-Related Functions were outlined, which includes the objects and people required to perform the weaning process. Finally, these were linked to their Object-Related Processes; properties and attributes of the objects and people involved relevant to the weaning process. Each component and any relevant constraints it brings to the weaning process are outlined below.

Functional Purpose: three purposes of the weaning process were identified that are met simultaneously throughout weaning. However, there may be times when purposes conflict, and one must take priority over the other – for example, improving a patient's health may involve an uncomfortable procedure, and so whilst care is taken to not cause excessive discomfort, some may still occur in service to improving the patient's health. Each purpose is explained below.

- *Maintain Quality & Safety of Care*: whilst weaning an ICU patient, it is important that the quality and safety of their care is maintained throughout. Maintaining the quality of care and the safety of care are combined here based on the discussions with clinicians that stated their linked nature, as safety is a component of providing quality care. However, there may be factors that only affects quality or safety, in which case these Purposes could be separated. This Purpose is constrained by all Value and Priority Measures, as there is a time pressure to move patients through ICU as quickly as possible whilst still being safe.
- *Improve Patient's Health*: the purpose of weaning is to extubate the patient so they can breathe on their own, and eventually leave the ICU and hospital. This is constrained by all Value and Priority Measures, as there is a need to consider a patient's long-term

health as well as what they are currently capable of handling. Early extubation may improve a patient's condition quicker, but it also increases the risk of reintubation, which can decrease a patient's health. However, whilst leaving the endotracheal tube in minimises the risk of reintubation, this exposes the patient to a risk of a ventilator-associated pneumonia and other issues such as ICU-acquired weakness.

- *Minimise Patient Discomfort*: whilst a patient is weaned, it is important they are kept as comfortable as possible. This is not only for the purpose of proving quality care, but also as patient mindset has been shown to influence recovery rates (Crum et al., 2017). This purpose is constrained by the Value and Priority Measures minimising time on ventilation, sedation, and time in ICU. For example, a patient may be comfortable on a high level of sedation, meeting the purpose of minimising patient discomfort, but this would conflict with the function of minimising the time on sedation and time in ICU. Increasing the length of sedation and time in ICU may negatively affect a patient's health, and so conflicts with the other Functional Purpose of improving patient health. Conversely, patients are likely to be uncomfortable when ventilated for extended periods of time. However, this discomfort is unavoidable if they are still not able to breathe without support, as minimising their time on ventilation here could risk extubation failure.

Values and Priority Measures: five measures represent the constraints between the Functional Purposes of the system whilst undergoing the weaning process (the Purpose-Related Functions).

- *Achieve spontaneous breathing*: a patient needs to regain the ability to breathe spontaneously (whilst still on respiratory support) before extubation can begin. This is a necessary step in the Functional Purpose of improving the patient's health, achieved via the Purpose-Related Functions of adjust sedation and adjust ventilation.
- *Minimise time on sedation*: as long-term sedation can be damaging to a patient (Kollef et al., 1998), it is important their time sedated is kept to a minimum. This is in service to all three Functional Purposes, as whilst sedation is important to maintaining the quality and safety of care, and alleviating a patient's discomfort, too much or too little sedation can have lasting ill-effects on their health. This Priority and Value Measure is achieved via the Purpose-Related Function of adjusting the sedation levels.
- *Minimise time on ventilation*: similarly to sedation, a patient should not stay on ventilation for too long, as prolonged ventilation can significantly worsen patient outcomes (Cox et al., 2009). Consequently, this Priority and Value Measure is in service to the three Functional Purposes in a similar manner – a patient's health must be improved and their discomfort kept minimal by minimising time on ventilation, but the quality & safety of their care cannot be compromised by the risk of extubating too early. It is achieved via the Purpose-Related Functions of adjusting the ventilator, the conducting of SBTs, and extubation.
- *Minimise risk of reintubation*: whilst reintubation can cause further harm to a patient and should be avoided (Thille et al., 2013a), the risk of reintubation will likely always be present to some degree. Otherwise, patients are left for too long on ventilator support, which also causes harm. This is in service to all of the Functional Purposes of the system. It is achieved via the Purpose-Related Functions of performing SBTs, which predict a patient's tolerance for breathing unassisted (Thille et al., 2013a), as well as the assess patient and adjust ventilation functions performed throughout weaning to avoid reintubation.
- *Minimise time spent in ICU*: not only should patients spend as little time in ICU as possible for the Functional Purposes of their own health and comfort, but doing so also allows the ICU to process as many patients as possible whilst avoiding overcrowding. These reasons are also interlinked; by avoiding overcrowding, patients can receive better quality & safety of care and comfort, which in turn aids in the improvement of their health. Consequently, this Priority and Value Measure is in service to all Functional Purposes and is achieved via all Purpose-Related Functions, as the trajectory of a patient must be considered over the course of their treatment.

Purpose-Related Functions: five functions were extracted from the patient workflow outlined in the previous analysis of steps in the weaning process, that are in service to the Values & Priority Measures.

- *Assess patient*: clinicians must assess the patient for overall suitability to continue in their weaning. This is therefore performed in service to all of the Values & Priority Measures, as the assessment allows the clinician to consider a patient's breathing, sedation, ventilation, risks, and time spent. Assess patient is achieved via the involvement of all Object-Related Processes, as to evaluate a patient's status requires a clinician to be available and located near a patient, their information, and the equipment settings.
- *Adjust ventilation*: to continue the weaning process, the clinician must adjust the ventilator settings to the appropriate level for the patient. This is in service to all Values & Priority Measures except for minimise time sedated, as the clinician is attempting to achieve spontaneous breathing whilst minimising risks and time spent on ventilation and in the ICU. It is achieved via the Object-Related Processes of equipment setting, location, and availability.
- *Adjust sedation*: similarly to adjust ventilation, the clinician must adjust the sedation of a patient to the appropriate level. This is in service to the Values & Priority Measures of achieve spontaneous breathing, minimise time sedated, and minimise patient time in ICU, as the clinician is attempting to increase the consciousness of a patient safely. It is achieved via the Object-Related Processes of equipment setting, location, and availability.
- *SBT*: as part of the weaning process, a clinician is likely to initiate an SBT to evaluate a patient's likelihood of a successful extubation. This is therefore in service to the Values & Priority Measures of minimise time on ventilation, minimise risk of reintubation, and minimise patient time in ICU. It is achieved via all Object-Related Processes, as a clinician must be available and located during an SBT to monitor the patient information and adjust the equipment settings.
- *Extubation/tracheostomy*: when the patient is deemed ready, the endotracheal tube is either removed or a tracheostomy is performed. This is in service to the Values & Priority Measures of minimise time on ventilation and total time in ICU, as all patients must eventually be extubated. It is achieved via all Object-Related Processes for the same reasons as the SBT Purpose-Related Function.

Object-Related Processes: four processes were identified that represent the properties/attributes of the Physical Objects.

- *Location*: where the ICU staff are present on the ward. For example, consultants are not always on the ward, but are expected to be no further than 30 minutes away whilst on call (GPICS, 2022). As wards have different cultures, who is expected to be on the ward and what they are expected to do varies. For example, in the UK ICU nursing of an intubated patient should always be 1-to-1, with one nurse per patient (GPICS, 2022). This Object-Related Process is therefore in service to all Purpose-Related Functions, as all Functions involve a staff member to be present. It is achieved by the Physical Object of ICU staff.
- *Availability*: ICU staff and patient observations are both defined by their availability, as who is present on the ward varies throughout the day. Relatedly, who provides an observation of a patient is related to who is available to make them. This Object-Related Process is in service to all Purpose-Related Functions, as staff and patient

observations being available allows assessments, adjustments, and procedures to be conducted. It is achieved via the Physical Objects of ICU staff and patient observations.

- *Patient information*: the specific details of a patient. This is in service to all Purpose-Related Functions as patient information is used when making decisions about a patient. It is achieved via combining the data from the Physical Objects of patient observations, EHR data, infusion pump, and ventilator.
- *Equipment setting*: the current and previous settings used for equipment. Similarly to patient information, this is in service to all Purpose-Related Functions, and achieved via the combination of data from the Physical Objects of patient observations, EHR data, infusion pump, and ventilator.

Physical Objects: five objects were identified that represent equipment or people involved in the weaning process.

- *ICU staff*: numerous staff members interact with patients during the weaning process. ICU is designed to be consultant-led (GPICS, 2022), but registrars, bedside nurses, doctors, and physiotherapists all play a role in patient healthcare. Consequently, the staff Physical Object is in service to the Object-Related Processes of location and availability, as these allow the staff to perform their work.
- *Patient observations*: a lot can be inferred about the status of a patient from observing them. Observing the patient reveals insights not captured within the EHR data, and is commonly referred to as 'eyeballing the patient.' These observations can be made by a consultant during an assessment, but can also be from bedside nurses, as well as the senior and junior doctors present on the ward. Consequently, patient observations are in service to the Object-Related Processes of availability, patient information, and equipment setting, as observations are made by available staff to update the patient's status.
- *EHR data*: similarly to observations, the weaning process involves the use of EHR data to make decisions. Consequently, it is in service to the Object-Related Processes of patient information and equipment setting, as unlike patient observations it can be updated automatically without always requiring staff to be available to do so (and therefore does not require the Object-Related Process of availability).
- *Infusion pump*: the equipment used to administer sedation to a patient. During weaning, it is regularly interacted with by a variety of ICU staff members, though local practice varies on which staff will do so. This Physical Object is in service to the Object-Related Processes of patient information and equipment setting.
- *Ventilator*: the equipment used to support patient breathing. It may have numerous settings, though typically has modes that progress from controlled (fully breathing for the patient) to assisted (detecting and activating when the patient breathes), where eventually the patient is able to breathe spontaneously (with minimal/low pressure support). It is in service to the Object-Related Processes of patient information and equipment setting.

Overall, the Abstraction Hierarchy demonstrates the complexity in the work involved in weaning a patient, even whilst excluding other work conducted as part of the ICU environment. There are many constraints present when considering the weaning of a patient, which are discussed in Section 5.

4.2.2. Information flow analysis

The daily workflow involved in monitoring patient progress was created from discussions with ICU clinicians. This was turned into a diagram in a similar way to the previous patient workflow map. It is shown in Fig. 3, along with the types of information available to the consultant during a ward round shown in the grey box. Note that this workflow does not include the incidental monitoring of a patient that happens throughout the day, such as by bedside nurses. There may also be differences on when ward rounds are conducted depending on the specific unit in question. Further, as the focus of this study is on how decisions are made and information is gathered by clinicians during the ICU weaning process, the figure is doctor-centric rather than patient-centric.

As can be seen, there is a daily flow of patient monitoring which typically involves three ward rounds. Ward rounds allow each patient to be assessed for their current progress, the likelihood of successfully continuing weaning, and the setting of weaning progress goals to be achieved in a given timeframe. As described by the interviewed clinicians, the morning round is primarily consultant-led, where the overarching goals for each patient are set given their current progress. The midday round may or may not involve the consultant, which aims to assess the progress of patients since the morning goals were set. The evening round is typically consultant-led and acts as a review of the day's progress. There may also be a night round led by a junior doctor.

As each patient is likely at a different stage of weaning, what decisions are made in each ward round varies, as well as how much attention is paid to each type of information. For example, the current state of the ICU environment is useful information to a consultant when a patient appears ready for extubation – if the ICU is particularly busy or is approaching the evening, a consultant may leave the patient until the next ward round to begin extubation, to ensure an adequate staffing level to monitor the process. As patients are rarely extubated overnight, consultants may also decide a patient who is close to extubation can be extubated before the next morning round, to reduce time on ventilation. This is because staying on ventilation too long can harm the patient, and the time between ward rounds can be long enough that a patient makes sufficient progress and so can continue weaning. Throughout the day, patients may also receive physiotherapy to aid in clearing the lungs of secretion, which can involve altering their respiratory support temporarily.

Observations from physiotherapists and bedside nurses are particularly important to consultants, as these staff members observe a patient's trajectory. Furthermore, nurses can provide feedback on subjective clinical assessments such as how well the patient has been coughing or how responsive they have been since a reduction in sedation, as these variables are not available in the EHR data. They may also prompt extra reviews of a patient outside of a ward round if they think it is beneficial to do so. Alongside this, consultants may discuss a patient with a variety of other team members, as shown in Fig. 4. The line weight indicates the frequency in which a consultant will seek information from each source during a ward round.

Overall, this process allows a patient to be assessed throughout the day. However, the ICU operates under the concept of the multidisciplinary team, with multiple experts giving input for their own specialist areas. It is therefore not always clear who is making which decision about a patient's weaning progress. For example, whilst the consultant can be seen as having the 'final say' over what should happen to the patient, they are unlikely to be the one to always implement the change, or the day-to-day decisions involved in taking care of a patient. This can instead be handled by junior doctors and the bedside nurses following the consultant's instruction, as well as physiotherapists who may temporarily alter the patient's respiratory settings to perform their work. Further, in some UK wards it is common for physiotherapists to be heavily involved in making decisions and creating weaning plans, especially for tracheostomy weaning, and so the consultant may take on a more supervisory role in these cases. Therefore, who implements what decision and who interacts with the patient's respiratory support can vary between wards and cultures.

Consultant decisions are also not always given as fully detailed instructions, depending on the culture of the ICU and the experience of the people working in it. For example, an experienced senior bedside nurse may be able to take relatively vague consultant instructions and implement them using their professional knowledge and experience.

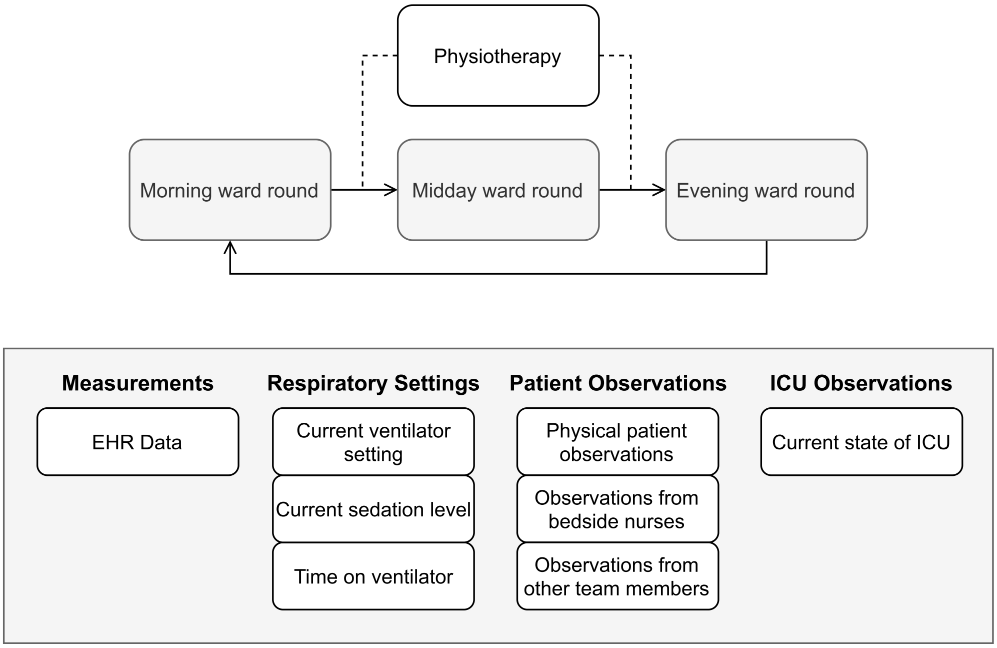

Fig. 3. A typical ward round for consultants in charge of intubated patients, and the information available to them during these rounds.

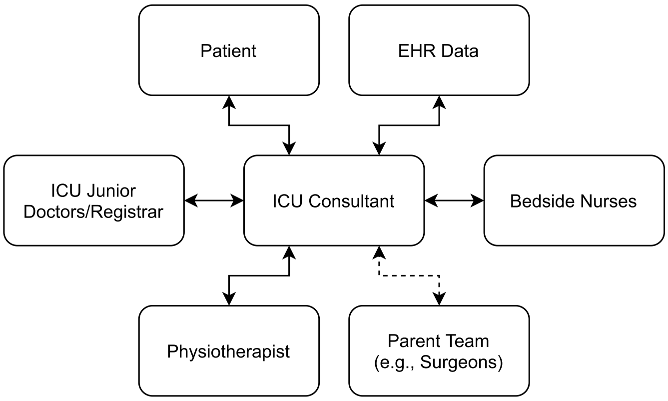

Fig. 4. The sources of information available to ICU consultants as described by the interviewed clinicians. Dashed lines indicate less frequency of use.

Therefore, whilst the overarching decision of how to progress a patient's weaning is specified by the consultant, how this is implemented and by whom may differ.

5. Discussion

This study explored the work context around weaning ICU patients from mechanical ventilation, both in terms of the decision-making tasks that make up this process, and the setting weaning takes place in. In doing so, areas where clinicians may benefit from the introduction of decision-support tools that are also mindful of any constraints that may affect their design could be identified. This was done by combining two analyses: a Work Domain Analysis to understand the constraints of the work system, and a Cognitive Task Analysis to understand the decision-making process of clinicians. A summary of the insights is presented in Table 6, and each is explained below.

5.1. *Insights from CTA*

To answer the first research question, what decision-making is involved in the weaning process, a CTA was performed. This outlined clinician's decision-making processes when weaning ICU patients from mechanical ventilation. In doing so, a number of insights were generated, which have implications for introducing decision-support tools. The first insight notes the inherent complexity of the weaning process. Numerous cognitive tasks of many differing types are involved throughout the process, from simple knowledge of the task to clinician's self-evaluating their decisions. This suggests there is a fluctuation in a clinician's cognitive workload depending on which step they are performing in the weaning process. For example, assessment stages where clinicians decide how well a patient is progressing involves the highest cognitive workload, as all types of cognitive process outlined by Bloom et al. (1956) are found here. Therefore, assessment steps could be a useful place to introduce decision-support tools to help reduce their cognitive workload.

However, a related insight reveals even laying out the steps undertaken during weaning was not simple. Within the workflow outlined in Fig. 1, there are many iterative loops involved where a clinician must consider whether a patient's status may deteriorate. Furthermore, there are several parallel processes that occur during weaning, such as the simultaneous adjustment of ventilation and sedation. Therefore, understanding each step in the weaning process is complicated by the interlinked nature of multiple variables that must be accounted for. Consequently, a decision-support tool introduced into the weaning process must be able to monitor several different variables and trajectories, that are likely occurring at the same time. A tool that only considers one aspect of the weaning process, such as only ventilation, is unlikely to be useful in these settings.

Relatedly, on top of the process being highly interconnected and iterative, weaning pathways between patients can be highly varied. Whilst many cases are simple and only require one (or even no) SBT and one extubation (Boles et al., 2007), there are still patients where this is not true. It can be difficult to distinguish between patients who will have a simple weaning process from those that will require more complicated care and closer monitoring. Whilst there are risk factors associated with complex weaning, such as age (Thille et al., 2013b), extubations expected to be successful go on to fail in around 10% of cases (Thille et al., 2013a). Therefore, a decision-support tool that can detect or make inferences on the complexity of a patient's weaning may prove useful to reduce extubation failure.

A final insight involves the amount and variety of information sources a clinician considers during the weaning process. Navigating

Table 6
A summary of insights gained and their implications for designing decision-support tools in this area.

Method	Insight	Application to decision-support tools
CTA	The weaning process comprises numerous complex cognitive tasks, where assessment stages likely contain the highest cognitive workload	Clinician workload could be reduced by designing tools to aid with assessment stages
	The weaning process contains several iterative loops and parallel processes, which are all interlinked	A tool would need to monitor several variables and processes at the same time
	The weaning process can be highly variable between patients, and it is difficult to predict how simple the process will be for a given patient	Predicting how complex a patient's weaning process is likely to be could be beneficial for clinicians
	The weaning process involves a high volume and variety of information from different sources for clinicians to consider and keep track of	Highlighting potential deterioration of a patient and contradictory/ambiguous results from varied information could be beneficial for clinicians
WDA	Decisions about weaning need to consider how long a patient should stay on ventilation to avoid adverse outcomes, e.g., extubation failure	Time on ventilation could be more accurately calibrated to a patient by designing tools to suggest when patients are ready for extubation
	Decisions about weaning need to consider both the current status of the patient as well as their previous statuses/trajectory	A tool would need to consider both the current status of the patient as well as their previous statuses
	Decisions about weaning need to consider a balance of patient comfort and speed of weaning	A tool would ideally need to consider patient comfort when suggesting when to progress weaning
	Decisions about weaning need to consider both the patient's weaning progress and the timing of when decisions are made by clinicians	Total weaning time may be reduced by designing tools to suggest when patients are ready to progress independently of ward rounds
	Decisions about weaning and the information discussed during ward rounds varies highly between patients	A tool would need to be carefully specified for when it is to be used and what results or variables it predicts
	Decisions about weaning are made as part of an multidisciplinary team, and so decision-making is a shared activity	A tool would need to be carefully specified for when it is to be used and by whom
	Decisions about weaning need to consider both the patient's weaning progress and the current ICU environment (e.g., staff levels)	Considering the time of day/current staffing levels when suggesting a patient is ready to progress may be beneficial for clinicians
Combined	There is a complex integration of the tasks performed for a specific patient's weaning process into the daily workflow of clinicians	Multiple clinicians may interact with a tool across their daily workflows, which may affect the types of interactions performed and information a tool needs to accommodate
	The multidisciplinary teams present in the ICU environment complicate who is making a decision and what their skills and roles are	A tool would need to carefully consider a variety of users during design to ensure it can be appropriately understood and used

this information is a complex task, especially when it can be contradictory or unclear. This is why, on top of the EHR data available for a patient, clinicians also observe the patient and discuss their thoughts within a multidisciplinary team. This distributes input into the decision-making across individuals, which allows for a consensus decision to be taken. Therefore, a decision-support tool that can aid in handling these different data sources may prove beneficial for clinicians. For example, a tool could highlight potentially contradictory information or ambiguous results, or detect patients at risk of deterioration based on the information available.

5.2. Insights from WDA

To answer the second research question, what are the constraints of the weaning process in ICUs, a WDA was conducted. This revealed the constraints that exist within the work context surrounding the weaning process. These involve the patient's trajectory, the use of ward rounds to check patients, the structure of a multidisciplinary team, and the general ICU environment.

A constraint relating to patient trajectory is how long they should stay on ventilation. If a patient is on for too long, it can lead to later health complications such as muscle weakness or ventilator-associated pneumonia (Bigatello et al., 2007). Conversely, if a patient is removed from ventilation too soon, they may need to be reintubated, which can also harm the patient (Thille et al., 2013b). Therefore, clinicians attempt to estimate the most appropriate time to extubate, which is not a binary decision but based on the probability of success. Consequently, an extubation readiness decision-support tool could prove beneficial to clinicians, by suggesting when a patient is likely to succeed extubation.

A second patient trajectory constraint involves the types of information a clinician uses to make a decision. Specifically, the clinician must consider both the current status of the patient and their previous statuses/trajectory throughout the weaning process. It is important for the clinician to consider both types of information, as they may suggest contradictory outcomes; a patient may appear ready to extubate now, but within the last 24 hours may have been unstable, suggesting otherwise. Therefore, a decision-support tool that considers the current status of a patient whilst accounting for their previous statuses may prove beneficial when making decisions about weaning progress.

A third patient trajectory constraint involves managing patient comfort against the speed of weaning. It is important that a patient is not in undue pain or stress during weaning; whilst they may be able to handle a faster weaning progress it could cause significant strain, so should be avoided. Therefore, a decision-support tool for aiding the weaning process should ideally consider whether a patient will be caused undue discomfort if a progression in their weaning is suggested.

Considering the use of a ward round to monitor patients, there is a constraint involved in the timing of rounds and the patient's weaning progress trajectory. Many patients make substantial improvements between ward rounds, but as a consultant typically offers input during a round, they may need to wait longer than necessary before a decision is made. However, the length of this delay depends on the culture of the specific ICU. For example, in some units, especially in the UK where there is a 1:1 nursing to patient ratio, the delay between a patient being ready and extubation may be shorter as a nurse can signal to the consultant outside of a ward round. Therefore, a decision-support tool that can suggest when a patient is ready to progress, independently of ward rounds, may help speed up the weaning process. However, such a tool would likely also need to be aware of other ICU constraints, such as the current staffing levels, to ensure its suggestions make sense given the current work environment.

A second constraint of the ward round is the variation in the content depending on the current patient. Ward rounds are different for each patient depending on their current status, so not all rounds will involve the same weaning progress discussions. For example, different information will be considered for a patient that has only recently had their initial underlying condition resolved as opposed to someone who is ready to begin an SBT. Therefore, it may not always be clear when or which type of decision-support tool is needed for a specific patient. Consequently, when designing a tool it is important to clearly indicate when it should be used and by whom, as well as what results or variable it predicts at what times. For example, if the tool is intended to predict extubation readiness, a bedside nurse would most likely only turn it on when the patient's initial condition is resolved, and then monitor its suggestions from this point onwards. During a relevant ward round, the nurse could then pass on their usual observations as well as the information from the tool to the consultant, to make an informed decision.

Considering the multidisciplinary team structure of ICUs, and specifically the extubation process, there is a constraint involved in who makes the overall decision to extubate (i.e., the consultant) and who operates the equipment and monitors the patient during extubation (i.e., doctors/nurses). The collaborative nature of ICUs allows decisions to be made using all available information, however this makes it difficult to introduce a decision-making tool as decision-making is shared across individuals. For example, it may be unclear who would interact with a decision-support tool, as a number of multidisciplinary team members with varied backgrounds and experiences could do so. Consequently, the design of a tool may have to consider a varied user base not specific to one type of medical professional, to ensure it is properly understood. Clarifying who should interact with the tool is also important, as otherwise the information from the tool may be ignored or improperly used.

Finally, considering the changing state of the ICU environment where weaning takes place, there is a constraint involved in weaning progress and the current ICU condition. For example, patients ready for extubation must wait until there is adequate staff availability, in case of complications. This is why patients are rarely extubated overnight, and instead wait until the following day. Therefore, a decision-support tool sensitive to the time of day and current staffing levels may provide more useful suggestions for when to extubate a patient.

5.3. Combined insights & potential applications of decision-support tools

To answer the final research question, what contextual design requirements can be gained from CTA and WDA analyses, it was important to first combine all the findings. Doing so allowed further insights to be made about the weaning process context, which revealed further contextual design requirements. For example, the interaction between the daily workflow of clinicians and the tasks they perform in the weaning process is a unique insight. There are multiple ways to view the work that takes place in an ICU setting; for example, what clinicians do in a typical day, and what they do specifically to wean a patient from mechanical ventilation. The key difference between these views is the time frame, as weaning may take longer than one clinician's day/shift and so will involve multiple people at different steps. This has implications for understanding what decisions are made, at what time, by who, and involving what information. For example, more than one clinician is involved in making decisions about a patient's weaning progress, which also spans across multiple daily workflows. Consequently, decision-support tools designed to help with the weaning process of specific patients must also consider how they interact within multiple clinician's daily workflow.

Expanding this further, another related combined insight is the impact of multidisciplinary teams. Similarly to the above, who is making a decision about a patient and when can be complicated to identify. Not only are several clinicians involved with one patient's weaning process, each will also have different skills and roles. In turn this makes it complicated to design decision-support tools to support weaning patients, as it is likely not enough to only consider one type of user. For example, careful specification in tool design is likely needed to handle being used by a variety of staff members, such as nurses and consultants and junior doctors.

Given the above insights, there are several potential areas where decision-support tools could help the weaning process. There are as follows:

- **Patient complexity classification**. It is sometimes difficult to predict how easily a patient will respond, as even planned extubations can fail. A tool that can predict the complexity of a patient's weaning progress may prove useful to clinicians deciding how cautiously they should progress with weaning.
- **Patient deterioration detection**. A similar area a tool may help clinicians is in predicting when a patient may deteriorate if a weaning step is currently performed. This could help to minimise the total time spent on ventilation, and reduce the adverse effects such as those associated with re-intubation.
- **Ventilation adjustment**. During the interviews, the consultants discussed the complexity of the ventilation systems. There are numerous settings, where a tool could automatically set the correct mode and parameters depending on the needs and input from the clinician. This could speed up the weaning process as the most advantageous ventilation mode could be selected at each stage.
- **SBT success prediction**. As successfully passing an SBT increases the chance a patient will successfully extubate, a tool to predict when a patient is likely to pass an SBT may help speed up the weaning process.
- **Weaning progress/extubation readiness**. Similarly to the above, a tool to indicate when a patient is ready to move to the next weaning step may help speed up weaning. This may also be specifically for predicting extubation readiness, as this is the stage where a high degree of harm can be caused if the wrong decision is made.

5.4. Design requirements for weaning decision-support tools

Given the above analyses, insights, and potential applications for decision-support tools, the final research question can now be answered: what contextual design requirements can be gained from these analyses. The following contextual design requirements have been generated, specifically focused on accounting for the context of weaning that should be considered during tool development. Due to the specific focus on ICU patient weaning within the UK setting, some requirements may not be as transferable to other contexts. This is flagged where appropriate throughout this section. Decision-support tools for aiding in the weaning of ICU patients from mechanical ventilation should be:

1. **usable by a variety of multidisciplinary team members.** It is not only consultants who make and implement decisions relating to patient weaning, and so it is important the tool is designed with a variety of staff members in mind, who each will vary in their levels and types of experience and knowledge. Who is involved in the weaning process may vary between ICUs and cultures, such as in the UK where senior bedside nurses can be given a high degree of autonomy over the ventilator settings depending on the ward culture. It is therefore important to understand the specific protocols a given ward uses to identify the correct user groups.
2. **clear who is responsible for using the tool and when.** ICUs are complex systems involving a variety of multidisciplinary staff members interacting with one another and technology, so it is important to ensure each member knows who is responsible for what interactions and decisions made with the tool.

3. **able to use information relating to ventilation and sedation progress in combination.** There are several parallel processes occurring during the weaning process, of which the adjustment of sedation and ventilation are two important ones. A tool in this process will need to be aware of both adjustments simultaneously, as they both influence the readiness of a patient to progress to the next weaning step.
4. **sensitive to a patient's trajectory.** As weaning involves a series of steps, it is important that a tool both understands the current and previous status of a patient, and can use this trajectory to make decisions about future time points. This is especially important as the weaning process is not always strictly linear, as patients may require adjustment back to a previous step if there is a deterioration in their status.
5. **able to alert clinicians to changes in a patient's trajectory.** As a singular patient's progress interacts with a variety of staff members and commonly takes place over a number of days, it is important that a tool can alert a clinician to a change in a patient's weaning condition. This can help clinicians identify the times when a patient is ready to progress to the next step, and hopefully reduce the total time on ventilation.
6. **sensitive to a patient's pain/stamina tolerance when suggesting decisions.** Increasing the levels of breathing initiated by a patient can be tiring, and progressing too quickly can lead to deterioration in their status. A tool involved in weaning should be sensitive that a patient may appear ready to progress from their EHR data, but there are also subjective considerations around their comfort levels to consider.
7. **sensitive to the time of day and staffing levels when suggesting decisions.** Whilst a decision about when to progress weaning can be made from a patient's data alone, it is important to consider the wider ICU environment. Patients require careful monitoring from staff members, and it is important that suggestions made by a tool are compatible with their current workload, or suggestions may be disregarded as unhelpful. The specific staffing levels and availability will vary between specific ward contexts, so it is important to understand the ward practices where the tool will be implemented.

Understanding these contextual design requirements will in turn aid the design of decision-support tools, especially in regards to those using artificial intelligence/machine learning. Despite the predictive capabilities of AI models, such systems have yet to be widely or successfully deployed in healthcare (Elwyn et al., 2013). One of the reasons for this is their lack of fit into the wider clinical context, as a system may be highly accurate but not designed in a way that allows clinicians to access its insights easily alongside their other work responsibilities. Using the contextual design requirements outlined here may help bridge this gap, as it is possible to see the types of approaches/AI models that may prove more successful in this setting even before development of a tool has begun.

For example, when designing an AI/ML tool for aiding in ICU patient weaning, an algorithm able to learn temporal dependencies may be particularly useful, such as temporal convolutional networks. A Temporal Convolutional Neural Network (TCN) is a family of neural network architectures designed for processing sequential data with a focus on capturing temporal dependencies. It addresses temporal dependencies in sequential data through several key architectural features, such as causal convolutions and dilations. Causal convolutions are convolutions where an output at time t is convolved only with elements from time t and earlier in the previous layer, whilst dilated convolutions enable an exponentially large receptive field. Further, it can also be augmented with residual layers to enable the networks to look very far into the past to make a prediction. For a detailed description of TCN architectures, see Bai et al. (2018). In the current use case, we could feed the patient data (e.g., vital signs) from the past 12 hours to the TCN in order for the network to consider the development of the patient, as well as the current state of the patient when making a prediction for weaning readiness. This shows that the TCN could satisfy the fourth design requirement that considers the knowledge of a patient's trajectory over time.

Similarly, the first requirement that the tool be usable by a variety of multidisciplinary staff members suggests an AI/ML tool will need the ability to explain itself differently depending on who is interacting with it, their role with the tool, and their knowledge of the weaning process. In doing so this may help a user understand the tool better and in turn increase their trust in it, as trust has been found to increase AI technology acceptance (Choung et al., 2023). However, there must also be consideration for how the tool adapts to different users. If the tool responds differently to different users, it should be made transparent how this is achieved and why. Increasing transparency has been found to increase trust in AI technologies, as users are able to better understand the tools they are interacting with (Shin et al., 2020). For example, allowing users to transparently see how the tool is adapting to them avoids confusion regarding what the tool is outputting and how this output should be interpreted. Establishing appropriate trust can however be a complex process, which in turn can affect how users interact and use AI technologies; for a more detailed discussion on the issues regarding trust, transparency, and AI technologies, see Glikson and Woolley (2020).

Overall, when such tools are further into development, they would require more specific design requirements to be created. However, these contextual requirements provide a useful starting point for development.

5.5. Limitations & future work

This study used opportunity sampling to collect the interviewed clinicians and publicly available guidelines, alongside a literature review. Consequently, analysis was limited to the types of data collected and could not utilise the full range of information sometimes expected from a workplace analysis. For example, it was not possible to observe the clinicians actively performing the weaning process, meaning no analysis of their specific strategies and decision-making could be performed. Instead, an exploratory approach was taken combining multiple methods (a WDA and a CTA) to provide an overview of the current weaning process. However, the goal of this study was to understand the general work context of the weaning process, to identify potential areas for introducing new decision-support tools which future projects can pursue. Future work could explore other methods and ways to model the weaning process to add to the insights generated here, as this helps to design better interventions (Salmon and Read, 2019). For the purposes of this study, the available data was able to generate general, contextual design requirements for tools associated with the weaning process. Specific design requirements will be necessary for future work when the type of decision-support tool has been decided, which could then extend the current analysis to include other data sources, such as observations.

Furthermore, this study primarily focused on the workflow and needs of consultants, however there are several other types of ICU staff involved in the weaning process who would likely interact with a decision-support tool, such as bedside nurses and physiotherapists. Consultants were chosen as the main focus as they make the final decisions for weaning, though a senior registrar was also included to help expand the viewpoints collected. Modelling the work system and its primary users via a WDA and a CTA represented an initial step in employing a user-centred design process for creating decision-support tools, where understanding the context is a critical step for designing human-centred AI (van Berkel et al., 2022). Using established methods for understanding the context of complex socio-technical systems allowed insights to be gained on what users may need from decision-support tools introduced to their work, but other methods could have provided further insights (such as focus groups and observations). Therefore, it is important to include other user groups in future development of decision-support tools in this area, especially for interface design, as well as a potential need to conduct further analyses of the context.

Following the above limitation, the sample of clinicians interviewed was small due to the nature of the opportunity sampling approach. Whilst the three interviews did provide rich insights into the nature of patient weaning, and each worked in different hospitals and ICU wards, the data likely contains biases that limit its generalisability. This is especially true given all three clinicians only worked in the NHS, and so could only provide insights into the UK context. In turn, the design requirements created are most relevant to the UK context, though these were created by synthesising the interview data with other literature data sources to widen their applicability. Therefore, care should be taken when applying these design requirements to different international contexts.

Another direction for future work involves the need to build on and apply the design requirements to the development and deployment of decision-support tools, to help ensure they are feasible and successful within their contexts. This is because, whilst this work created contextual design requirements for ICU ventilator weaning, this is only the first step in creating user-centred decision-support tools. To do so, it is important to take a collaborative approach to applying these requirements to a specific tool design, by incorporating both stakeholders and experts with different domain knowledge throughout the development process. For example, it is important to continue to include consultant's feedback on the design as it is being built, so that it continues to match both their needs and fit their working environment. It is also important to extend the stakeholders involved to include other parties who will be affected by the tool's introduction, such as nurses and physiotherapists. To ensure stakeholder feedback is well integrated into the design, it is important for domain experts to also be involved throughout development who can provide actionable input on ways to incorporate stakeholder feedback and any wider concerns. These may include those with a human factors, legal, ethical or sociological background, whose level of involvement will vary depending on the tool and context in question. In doing so, future work developing decision-support tools for ICU weaning can consider the context and its users, by using the abstracted design requirements outlined here as an initial starting point.

A final direction for future work is to consider what the interface of decision-support tools for ICU patient weaning should look like. Whilst this paper considers the more abstract concepts of how users may wish to interact with such tools, these require application to concrete designs. This can be done by incorporating ecological interface design principles during the development of decision-support tools (Giang et al., 2010). Using the findings from the Abstraction Hierarchy, the constraints outlined can be applied into the design of the interface itself, so that the user is always aware of what is and is not possible in the given context. For example, knowing a clinician's decision on when to wean is constrained by their need to synthesise different information from a variety of sources, suggests an interface for a decision-support tool should be able to display a varying amount of patient information depending on what is needed in the current context. However, future work is needed to understand the most appropriate ways to design the tool's interface around the constraints of the system, to aid the user in performing their tasks.

6. Conclusion

Due to the complexities in weaning patients from mechanical ventilation, there has been an interest in developing decision-support tools to aid in the weaning process. However, many attempts to integrate new decision-support tools into clinical practice have been unsuccessful, particularly due to a lack of consideration for the wider work context. To ensure such tools will prove effective in clinical practice, it is important to understand the wider work system surrounding the tasks involved, to identify areas where tools are likely to provide needed benefits, as well as create contextual design requirements. This study analysed the constraints and affordances present in the work context, and the tasks involved in the weaning process, to identify areas where decision-support tools may aid clinicians. A series of contextual design requirements are suggested, which future researchers can use when designing tools for this setting. These requirements highlight the need to understand the specifics of the context that decision-support tools are designed for, to increase the success rate of their adoption into clinical practice. By understanding the work context surrounding the weaning process, it is possible to employ a human-centred perspective during development, which is particularly useful for decision-support tools using AI/ML approaches.

CRediT authorship contribution statement

Nathan Hughes: Conceptualisation, Methodology, Results, Writing. **Yan Jia:** Conceptualisation, Methodology, Writing. **Mark Sujan:** Conceptualisation, Methodology, Writing. **Tom Lawton:** Conceptualisation, Writing. Ibrahim **Habli:** Conceptualisation, Writing. **John McDermid:** Conceptualisation, Writing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Ashoori, M., Burns, C.M., d'Entremont, B., Momtahan, K., 2014. Using team cognitive work analysis to reveal healthcare team interactions in a birthing unit. Ergonomics 57, 973–986.

Austin, E., Blakely, B., Salmon, P., Braithwaite, J., Clay-Williams, R., 2022. Identifying constraints on everyday clinical practice: applying work domain analysis to emergency department care. Hum. Factors 64, 74–98.

Bai, S., Kolter, J.Z., Koltun, V., 2018. An empirical evaluation of generic convolutional and recurrent networks for sequence modeling. arXiv preprint. arXiv:1803.01271.

Bigatello, L.M., Stelfox, H.T., Berra, L., Schmidt, U., Gettings, E.M., 2007. Outcome of patients undergoing prolonged mechanical ventilation after critical illness. Crit. Care Med. 35, 2491–2497.

Bisantz, A.M., Mazaeva, N., 2016. Work domain analysis using the abstraction hierarchy: two contrasting cases. In: Applications of Cognitive Work Analysis. CRC Press, pp. 63–82.

Bloom, B.S., Engelhart, M.D., Furst, E.J., Hill, W.H., Krathwohl, D.R., 1956. Taxonomy of Educational Objectives: The Classification of Educational Goals. Handbook 1: Cognitive Domain. McKay, New York.

Boles, J.M., Bion, J., Connors, A., Herridge, M., Marsh, B., Melot, C., Pearl, R., Silverman, H., Stanchina, M., Vieillard-Baron, A., et al., 2007. Weaning from mechanical ventilation. Eur. Respir. J. 29, 1033–1056.

Cheng, K.H., Tan, M.C., Chang, Y.J., Lin, C.W., Lin, Y.H., Chang, T.M., Kuo, L.K., 2022. The feasibility of a machine learning approach in predicting successful ventilator mode shifting for adult patients in the medical intensive care unit. Medicina 58, 360.

Chockalingam, T., 2015. Weaning and extubation. J. Lung Pulmonol. Respir. Res. 2, 00043.

Choung, H., David, P., Ross, A., 2023. Trust in ai and its role in the acceptance of ai technologies. Int. J. Hum.-Comput. Interact. 39, 1727–1739.

Chromik, M., Butz, A., 2021. Human-xai interaction: a review and design principles for explanation user interfaces. In: Human-Computer Interaction–INTERACT 2021: 18th IFIP TC 13 International Conference. Bari, Italy, August 30–September 3. In: Proceedings, Part II, vol. 18. Springer, pp. 619–640.

Clark, R.E., Feldon, D.F., Van Merrienboer, J.J., Yates, K.A., Early, S., 2008. Cognitive task analysis. In: Handbook of Research on Educational Communications and Technology. Routledge, pp. 577–593.

Cox, C.E., Martinu, T., Sathy, S.J., Clay, A.S., Chia, J., Gray, A.L., Olsen, M.K., Govert, J.A., Carson, S.S., Tulsky, J.A., 2009. Expectations and outcomes of prolonged mechanical ventilation. Crit. Care Med. 37, 2888.

Crum, A.J., Leibowitz, K.A., Verghese, A., 2017. Making mindset matter. BMJ 356.

Elwyn, G., Scholl, I., Tietbohl, C., Mann, M., Edwards, A.G., Clay, C., Légaré, F., Weijden, T.v.d., Lewis, C.L., Wexler, R.M., et al., 2013. “Many miles to go…”: a systematic review of the implementation of patient decision support interventions into routine clinical practice. BMC Med. Inform. Decis. Mak. 13, 1–10.

Fackler, J.C., Watts, C., Grome, A., Miller, T., Crandall, B., Pronovost, P., 2009. Critical care physician cognitive task analysis: an exploratory study. Crit. Care 13, 1–8.

Frutos-Vivar, F., Esteban, A., Apezteguía, C., Anzueto, A., Nightingale, P., González, M., Soto, L., Rodrigo, C., Raad, J., David, C.M., et al., 2005. Outcome of mechanically ventilated patients who require a tracheostomy. Crit. Care Med. 33, 290–298.

Giang, W., Santhakumaran, S., Masnavi, E., Glussich, D., Kline, J., Chui, F., Burns, C., Histon, J., Zelek, J., 2010. Multimodal interfaces: Literature review of ecological interface design, multimodal perception and attention, and intelligent adaptive multimodal interfaces. Defence R&D Canada Contract Report, 1–269.

Glikson, E., Woolley, A.W., 2020. Human trust in artificial intelligence: review of empirical research. Acad. Manag. Ann. 14, 627–660.

GPICS, 2022. Guidelines for the provision of intensive care services. www.ficm.ac.uk/standardssafetyguidelinesstandards/guidelines-for-the-provision-of-intensive-care-services (Accessed 22 September 2023).

Gulliksen, J., Göransson, B., Boivie, I., Blomkvist, S., Persson, J., Cajander, Å., 2003. Key principles for user-centred systems design. Behav. Inf. Technol. 22, 397–409.

Hsieh, M.H., Hsieh, M.J., Cheng, A.C., Chen, C.M., Hsieh, C.C., Chao, C.M., Lai, C.C., Cheng, K.C., Chou, W., 2019. Predicting weaning difficulty for planned extubation patients with an artificial neural network. Medicine 98.

Jia, Y., Kaul, C., Lawton, T., Murray-Smith, R., Habli, I., 2021. Prediction of weaning from mechanical ventilation using convolutional neural networks. Artif. Intell. Med. 117, 102087.

Kilgore, R.M., ST, O., et al., 2016. From work domains to worker competencies: a five-phase cwa. In: Applications of Cognitive Work Analysis. CRC Press, pp. 29–62.

Knisely, B.M., Joyner, J.S., Rutkowski, A.M., Wong, M., Barksdale, S., Hotham, H., Kharod, K., Vaughn-Cooke, M., 2020. A cognitive decomposition to empirically study human performance in control room environments. Int. J. Hum.-Comput. Stud. 141, 102438.

Kollef, M.H., Levy, N.T., Ahrens, T.S., Schaiff, R., Prentice, D., Sherman, G., 1998. The use of continuous iv sedation is associated with prolongation of mechanical ventilation. Chest 114, 541–548.

Krinsley, J.S., Reddy, P.K., Iqbal, A., 2012. What is the optimal rate of failed extubation? Crit. Care 16, 1–5.

Laato, S., Tiainen, M., Najmul Islam, A., Mäntymäki, M., 2022. How to explain ai systems to end users: a systematic literature review and research agenda. Internet Res. 32, 1–31.

Marti, J., Hall, P., Hamilton, P., Lamb, S., McCabe, C., Lall, R., Darbyshire, J., Young, D., Hulme, C., 2016. One-year resource utilisation, costs and quality of life in patients with acute respiratory distress syndrome (ards): secondary analysis of a randomised controlled trial. J. Intensive Care 4, 1–11.

Miller, T., 2019. Explanation in artificial intelligence: insights from the social sciences. Artif. Intell. 267, 1–38.

Ossai, C.I., Wickramasinghe, N., 2021. Intelligent decision support with machine learning for efficient management of mechanical ventilation in the intensive care unit–a critical overview. Int. J. Med. Inform. 150, 104469.

Perkins, G.D., Mistry, D., Gates, S., Gao, F., Snelson, C., Hart, N., Camporota, L., Varley, J., Carle, C., Paramasivam, E., et al., 2018. Effect of protocolized weaning with early extubation to noninvasive ventilation vs invasive weaning on time to liberation from mechanical ventilation among patients with respiratory failure: the breathe randomized clinical trial. JAMA 320, 1881–1888.

Pham, T., Heunks, L., Bellani, G., Madotto, F., Aragao, I., Beduneau, G., Goligher, E.C., Grasselli, G., Laake, J.H., Mancebo, J., et al., 2023. Weaning from mechanical ventilation in intensive care units across 50 countries (wean safe): a multicentre, prospective, observational cohort study. Lancet Respir. Med. 11, 465–476.

Rasmussen, J., Jensen, A., 1974. Mental procedures in real-life tasks: a case study of electronic trouble shooting. Ergonomics 17, 293–307.

Reising, D.V.C., 2000. The abstraction hierarchy and its extension beyond process control. In: Proceedings of the Human Factors and Ergonomics Society Annual Meeting. SAGE Publications Sage CA, Los Angeles, CA, pp. 194–197.

Rudowski, R., East, T.D., Gardner, R.M., 1996. Current status of mechanical ventilation decision support systems: a review. Int. J. Clin. Monit. Comput. 13, 157–166.

Salmon, P.M., Read, G.J., 2019. Many model thinking in systems ergonomics: a case study in road safety. Ergonomics 62, 612–628.

Shin, D., Zhong, B., Biocca, F.A., 2020. Beyond user experience: what constitutes algorithmic experiences? Int. J. Inf. Manag. 52, 102061.

St-Maurice, J.D., Burns, C.M., 2017. Modeling patient treatment with medical records: an abstraction hierarchy to understand user competencies and needs. JMIR Hum. Factors 4, e6857.

Thille, A.W., Cortés-Puch, I., Esteban, A., 2013a 19, 57–64. Weaning from the ventilator and extubation in icu. Current opinion in critical care.

Thille, A.W., Richard, J.C.M., Brochard, L., 2013b. The decision to extubate in the intensive care unit. Am. J. Respir. Crit. Care Med. 187, 1294–1302.

Tsai, W.C., Liu, C.F., Lin, H.J., Hsu, C.C., Ma, Y.S., Chen, C.J., Huang, C.C., Chen, C.C., 2022. Design and implementation of a comprehensive ai dashboard for real-time prediction of adverse prognosis of ed patients. In: Healthcare, MDPI, p. 1498.

van Berkel, N., Tag, B., Goncalves, J., Hosio, S., 2022. Human-centred artificial intelligence: a contextual morality perspective. Behav. Inf. Technol. 41, 502–518.

Vicente, K.J., 1999. Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer-Based Work. CRC Press.

Wunsch, H., Wagner, J., Herlim, M., Chong, D.H., Kramer, A.A., Halpern, S.D., 2013. Icu occupancy and mechanical ventilator use in the United States. Crit. Care Med. 41, 2712–2719.

Yang, Q., Steinfeld, A., Zimmerman, J., 2019. Unremarkable ai: fitting intelligent decision support into critical, clinical decision-making processes. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, pp. 1–11.

Zein, H., Baratloo, A., Negida, A., Safari, S., 2016. Ventilator weaning and spontaneous breathing trials; an educational review. Emergency 4, 65.