Modelling Driver Decisions to Improve Port Traffic Management During Critical Situations

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We explore the idea that treating human decisions according to meaning processing approaches to cognition can lead to more satisfying management of real-world situations. We do this by attempting use the model of Flach & Voorhorst (2020) to improve the results of system theoretic process analysis (STPA) of traffic management in a busy port area of the Netherlands.

The study is ongoing and will interest researchers and practitioners looking to account for human factors in systems engineering, port and traffic managers implementing technological solutions, and those interested in ecological psychology and STAMP paradigms. The study is part of the EU project SAFEWAY.

The real-world challenge

Trucks delivering containers to a shipping terminal often need to pass by entrances to other terminals in order to reach their destination. If one of the bypassed terminals must close due to IT failures, high winds or capacity issues, trucks waiting to deliver containers can build up outside its entrance and block the passage of other trucks. To solve the problem, port management use road signs to divert incoming trucks headed for closed terminals to a holding area situated away from the entrance of the closed terminal. In practice, many of the truck drivers ignore the diversions and still head for the closed terminal. The existing road layout is such that trucks cannot be physically channeled to the holding area. Management want to know how to manage the situation by other means.

This real-world challenge concerns how to control driver actions in a complex sociotechnical system (Vicente 1999). It is becoming increasingly popular to frame such challenges using the Systems Theoretic Accident Model and Processes (STAMP; Leveson, 2012) paradigm, and analyse them using system-theoretic process analysis (STPA; Leveson & Thomas, 2018). In STPA, the analyst begins by defining **losses** to be avoided in the system (e.g. delay to container deliveries), system **hazards** that can could result in losses (e.g. roads blocked by trucks), and **system constraints** that must be controlled to avoid hazards (e.g. trucks must not block roads). The analyst then maps purposeful actions and information flows between all actors and technologies in the system, before identifying for each actor **unsafe control actions** that if performed could violate system constraints. Finally, **loss scenarios** are identified to explain why people or technologies could act "unsafely". These scenarios can then inform system improvements.

The methodological challenge

A central question in STPA is: What would make human or technological actors in the system perform **unsafe control actions**? Human actors are central to any sociotechnical system, but the STPA handbook provides little guidance on how analysts should model human perception and action (Leveson & Thomas, 2018). Several attempts have been made to elaborate this aspect of STPA (Thornberry, 2012; Montes, 2016; France, 2017), of which the extension described by France

(2017) has been popular. France's (2017) model of human control as summarized by Figure 1.

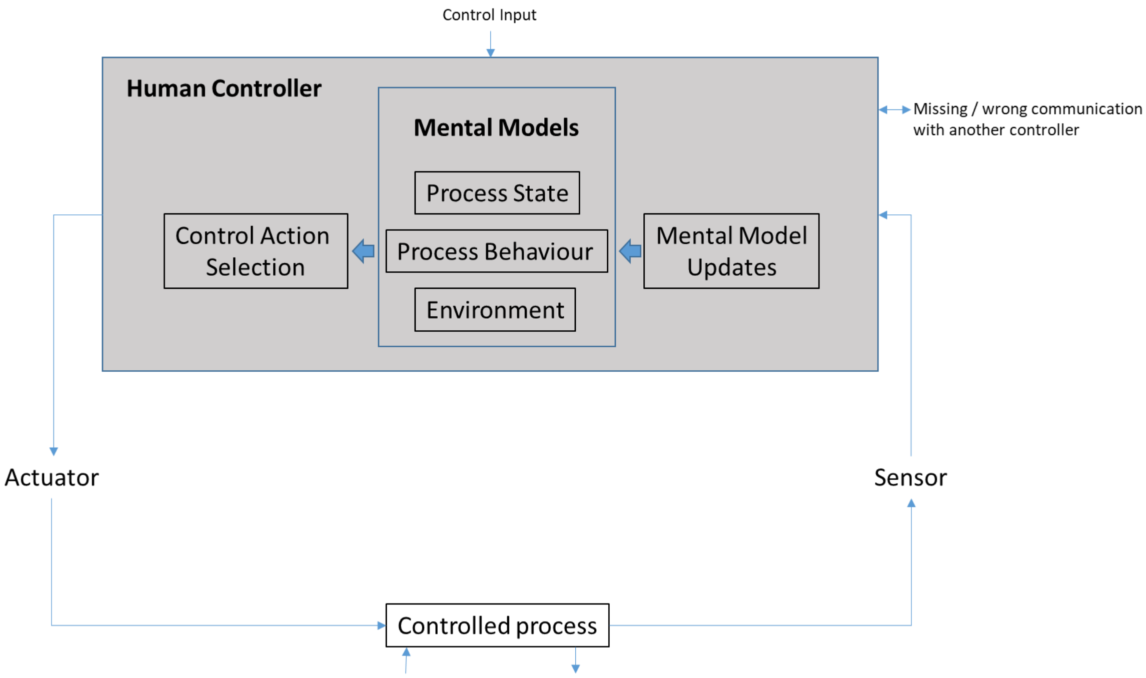

Figure 1. Model of human control used in "Engineering for humans". Adapted from France (2017).

In line with this model, France (2017) includes a set of questions analysts should ask when considering scenarios that could explain unsafe control actions. These are summarized in Table 1.

Table 1. Prompts analysts can use to consider scenarios that could cause unsafe control actions and system losses (France, 2017)

Main question	Prompts
How did the operator choose which action to perform?	• How did operator make their decision? • What goals were there? • Multiple/conflicting goals? • Designer vs. operator goals? • Available action alternatives? • Was the decision making skill-based (was a familiar action attempted when not appropriate?), rule-based (which rules were applied?), or knowledge based (what mental model of system or process?) • How were mental simulations of potential actions and consequent decisions influenced by time pressure, fatigue, workload etc.
What does the operator know or believe about the system?	• What mental models («cognitive representations of the world») did the operator have about: - process state? Model mismatch, mode error, mode change triggers - process behaviour? "Why is it doing that?", "what will it do next?", "what actions are available in current mode?" "How will inputs affect system behaviour?" - environment? Familiar or novel? Weather, complexity of situation, beliefs about other controller actions and mindsets
How did the operator come to have their current knowledge or beliefs?	• What difficulties are there in creating and maintaining mental models? • What properties of system or sensor information are most salient? • What feedback and input does the operator expect or think they should monitor? • What do they not expect or not monitor? • Effort for operator to access needed information?

The advantages of France's (2017) extension to STPA is that it models human control in a way that is both aligned with STPA terminology and accessible to engineers, such that they might account for human factors in their designs. Given the growing popularity of STPA, however, the modelling of human control has received little attention in the academic literature. In particular, there have been no attempts to conduct STPA while modelling human control using concepts that are explicitly aligned with models of human perception and control action in real-world environments, such as naturalistic decision-making (Klein, 2017), ecological psychology (Gibson, 2015) or dynamic human control (Jagacinski & Flach, 2009). These approaches have recently been collected, developed and espoused in a single model – the **meaning processing approach** to human cognition – but no attempts have been made to extend STPA and account for human control using this approach (Flach & Voorhorst, 2020).

The meaning processing approach

According to the meaning process approach, cognition is not located within the controller, but emerges from the ongoing interaction between a person and their ecology. In addition, cognitive emergency is usefully thought of as occurring in three dynamically interacting fields: satisfying, specifying and affording. The idea is summarized in Figure 2.

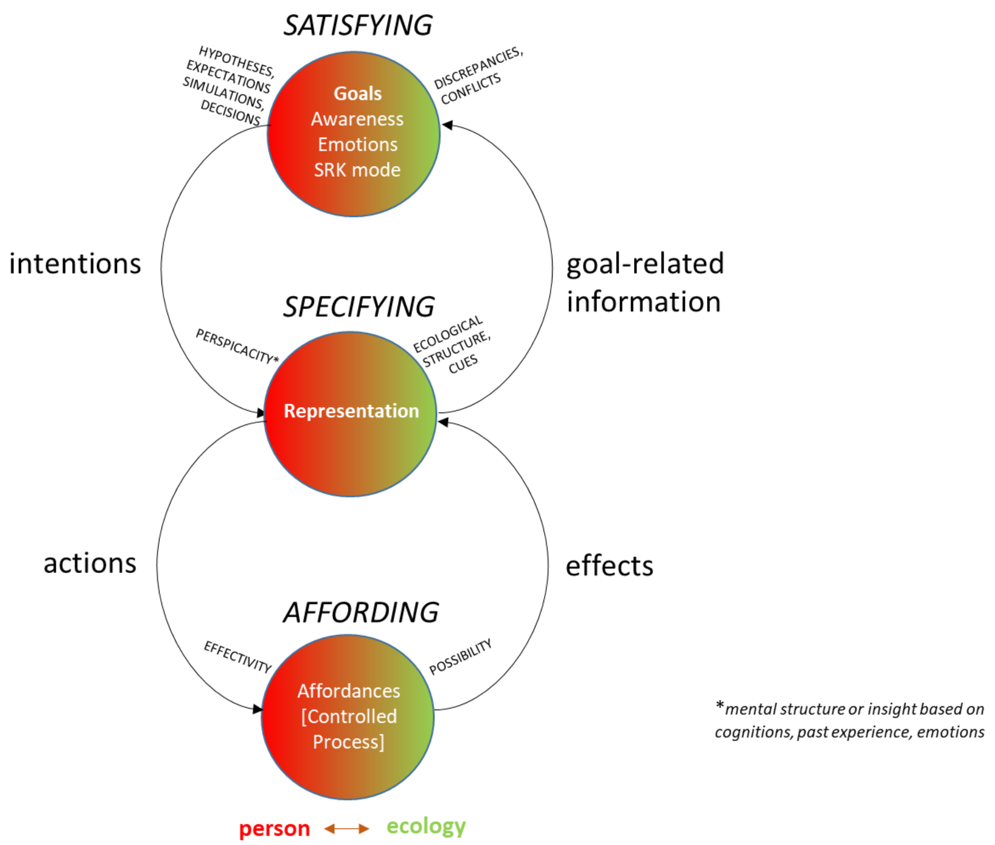

Figure 2. The meaning processing approach to human cognition. Adapted from Flach & Voordhorst, 2020. SRK = Skills-, Rules- or Knowledge-based, after Rasmussen (1983).

According to this approach, the person does not control a process like technology does, with internal algorithms, triggering actuators and responding to sensors (compare Figure 1 and 2). As France (2017) herself noted, human decision making cannot be explained by an internal algorithm. It is affected by emotions, fatigue, and awareness of goal discrepancies, ideas about the past and future, and intentions of other actors. The meaning processing approach is explicit about this, detailing how the person attends and acts based on what matters or *meaning*. It stresses that people often behave *abductively* in complex sociotechnical systems, i.e. approach goals through a process of trial and error in which they evolve strategies by learning from the effects of those strategies on goal discrepancies (costs). Purposeful action (control) evolves the system towards goals on basis of effects of actions on *representations* of the system. We attempt to summarize the key aspects of the meaning processing approach here:

1. In line with control theory, a person seeks to satisfy by achieving goals, evolving hypotheses, expectations and decisions in response to the (potential) costs of goal discrepancies. The process of **satisfying** emerges from the interaction of the person (e.g. physiology, experience, competence, mental and emotional state) and discrepancies apparent from surrounding ecology. Both ecology (e.g. signs, signals) and the person (e.g. fatigue) will influence whether decision-making is skill-, rule- or knowledge-based (Rasmussen, 1983).

1. **Specifying** the goal-related information and how to convert goal-related intentions to actions on the surroundings, involves representations emerging from the interaction between mental and ecological structure, in line with Gibson (2015).
2. Representations are influenced by actions to perceive affordances[1] in the ecology (Gibson, 2015). When conceived of as **affording**, actions on controlled processes depend both on the individual's ability to realize the possibilities that affordances offer, and on the availability of those affordances in the ecology. People perceive meaningful affordances i.e. when operating in-the-loop will not always be mindful about a whole controlled process.

AIMS

We aim to assess the feasibility and value of basing STPA-analyses of human actors on the meaning processing approach to cognition. So far, we have:

1) Used STPA to analyse the system of people, technology, infrastructure and procedures working to achieve orderly and efficient contingency parking on terminal closure.
2) Explored how the analysis might be improved by modelling human control as perception and action loops with dynamic coupling of ecological and psychological components, in line with the meaning processing approach to cognition (Flach & Voorhorst, 2020).

We wish to go on and test the feasibility of using meaning processing approach in STPA by using it to structure interviews with actors who decide and act in the study system. This will be reported at a later date.

METHOD

STPA analysis was performed on the study system defined under "The real world challenge" using the method of Leveson & Thomas (2018). The analysis was informed by port documents and reports, and three two-hour interviews with two representatives of port management, structured using Leveson & Thomas (2018). To

[1] Affordances are aspects of the real ecology that offer possibilities of goal-related action on a system, but they are of no use unless the individual can use them effectively.

identify possible loss scenarios involving human actors during the analysis, we structured our thinking of human perception and action according to France (2017). Following the analysis, we reflected on how an alternative STPA analysis could be structured to better account for the meaning processing approach to cognition (Flach & Voorhorst, 2020). We also sought to identify and possibly illustrate the potential value of developing STPA using such an approach.

RESULTS of STPA ANALYSIS

The STPA analysis is reported in full in Deliverable 4.2 of the EU project SAFEWAY. To summarise. we identified the following:

- Ten system constraints (SC) that if enforced would help avoid system states that could cause collisions, ship delays or loss of reputation (i.e. system losses). Examples of system constraints are SC1: *Drivers must not drive to a closed terminal instead of car park*; SC2: *No more than X drivers can head to a terminal Y minutes before it closes*.
- Control actions and information flows among the following system components: truck drivers, their employers (transporters), port police, road inspectors, parking staff, port management, on-site coordinators contracted by port management, traffic controllers, and re-routing measures. These are shown in Figure 3.
- 92 unsafe control actions that could violate the ten SCs identified. Unsafe control actions were identified by analyzing how each control action (numbered in brown in Figure 3) could be "unsafe" when carried out, when not carried out, or when carried out too soon or too late. An example of an unsafe control action when control action **14** is carried out is "*Driver tells other drivers via social media to drive to closed terminal*".
- Over 400 scenarios – situations in that would make unsafe control actions likely. In generating loss scenarios, human control was modelled using France's (2017) extension of STPA, i.e. prompts in Table 1 were answered using our knowledge of the system and understanding of truck drivers' situation. Loss scenarios generated for the control action "*Truck driver drives to terminal that is closed or about to close*" (see **13** in Figure 3) are given in Table 2.

To complete the analysis for port management, we designed 29 measures which together would help to avoid all 400+ loss scenarios, maintain system constraints and achieve the aim of port managers. These were derived directly from the loss scenarios e.g. "*Direct driver attention to re-routing measures*" for the first scenario in Table 2 "*Driver does not notice re-routing*".

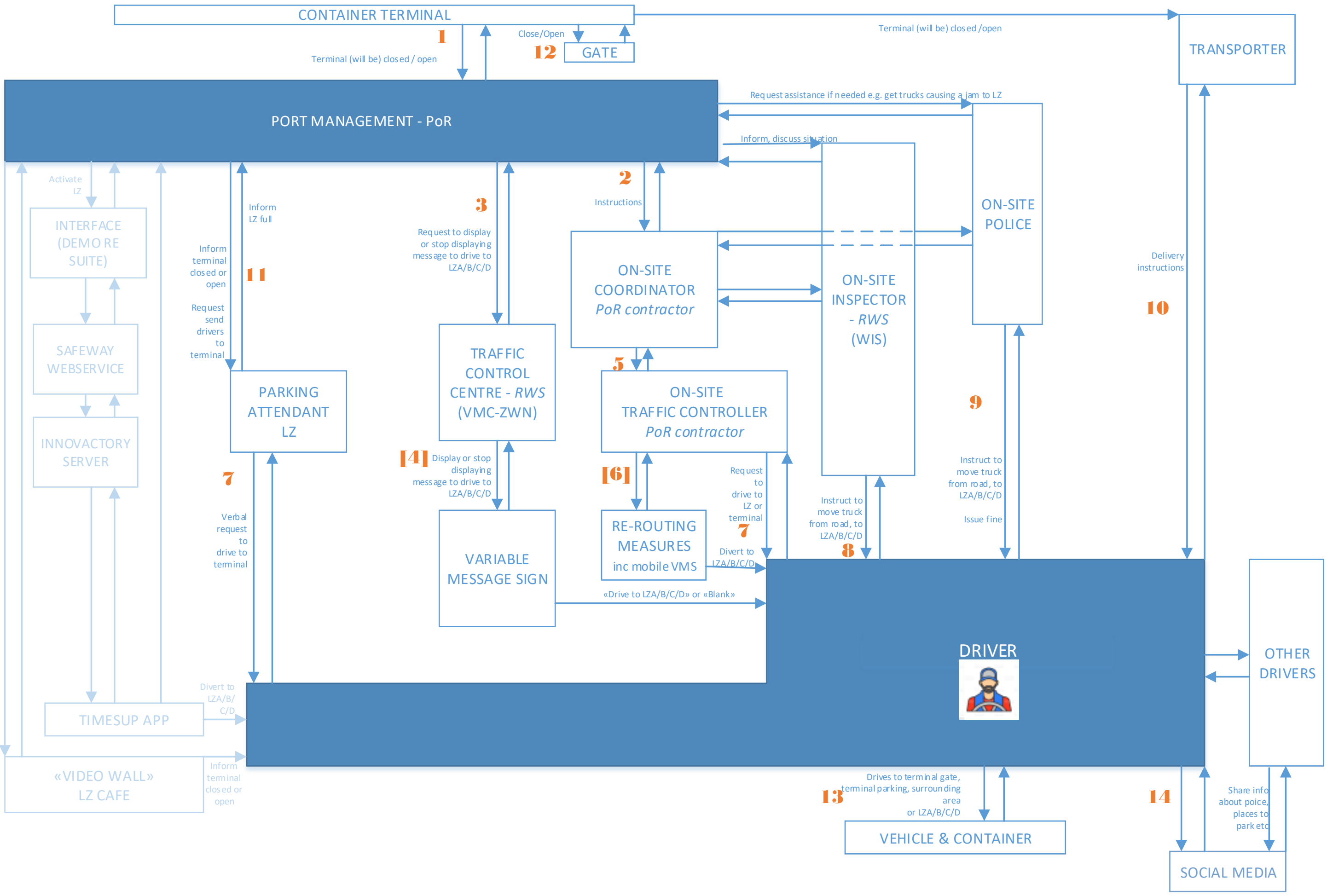

Figure 3. Control structure for the system involved in managing Truck Buffer Scenario. LZ = Landing Zone or holding area; RWS, state road admin; PoR, port management; VMS, variable message sign; WIS, state road inspector, VMC-ZWN regional traffic control center dealing with traffic on roads leading to/from port.

Table 2. Scenarios explaining why drivers could act "unsafely" by driving to a container terminal that is closed or about to close; analysis structured by French (2017)

Driver does not notice re-routing measures or signs
Re-routing measures have not been set out
Driver does not know terminal closed or will close, or when it will close
Driver is confused by conflicting messages from VMS, re-routing measures or Traffic Controllers
Driver attempting to follow re-routing measures to holding area takes wrong turn by accident
Driver believes they can still enter the terminal before it closes
Driver believes terminal is about to re-open
Driver bases action on past experience, when they could queue outside the terminal or park on nearby roads
Driver does not believe that the quickest way to enter the closed terminal is to head for the holding area
Driver heading for another terminal stops at the terminal because of a road blockage
Driver learns from Transporter or Other Drivers that terminal will close but they can enter if they ignore re-routing
Terminal closes suddenly
Driver instructed to head for terminal by Inspectors, Park Attendant or Traffic Controllers
No information given that terminal has closed, will close or when
Inadequate information about need to re-route to holding area or how to do so
No information about negative outcomes of ignoring re-routing at time and place where decision is made
Information about benefits of ignoring re-routing (e.g. jump ahead of queue, save time)
Inconsistent messages from Other Drivers, Transporters, VMS, signs etc. about need to re-routing or fairness of re-route
Driver gets no information on sudden closure when there has been no time to set out re-routing
Driver given incorrect time for terminal closure or terminal needs to change time of closure
Driver gets no feedback that they have taken a wrong turn mistakenly or deliberately
Driver, Transporters get no information about costs of ignoring re-routing measures.

MODELLING HUMAN CONTROL USING THE MEANING PROCESSING APPROACH

In line with the meaning processing approach in Figure 1, we recognized that answers to any one of the three questions in Table 1 also provide answers to the other two questions. For example, what the operator believes about the system affects which action they choose to perform. Reflecting on how unsafe human controller actions could be additionally explained using the meaning processing approach, we therefore identified a single set of prompts to generate answers to a single three-part question;

What is the actor trying to achieve in the system, why (how is the system represented), and how (what affordances are relevant)?

New prompts identified are shown in the left-hand column of Table 3. To illustrate their utility, the new prompts were tested by generating insight related to the single unsafe control action "*Truck driver drives to terminal that is closed or about to close*" (see control action **13** in Figure 3). The results are shown in the right-hand column of Table 3.

The insights are not stated as loss scenarios, but descriptions that *consolidate* and deepen the loss scenarios in Table 2. For example, the first loss scenario in Table 2 is "Driver does not notice re-routing". Table 3 consolidates and adds that this might happen if the operator is in a predominantly "skill-based" mode, e.g. they are operating "on autopilot" because they are familiar with the route or have many simultaneous tasks.

The insights in Table 3 also *supplement* the findings in Table 2. For example, they imply that drivers may wish to drive directly to the terminal to merely perceive its status for themselves ("act to perceive"). As part of satisfying, drivers may indeed seek out or attend to any affordance that could allow them to adapt and move closer to their main goal. This could include contacting colleagues or managers to identify workarounds, or continuing on roads leading to terminals to see how close to the terminal they can get. Althernatively, if they have time and are tired, they may choose to stop on way to port to eat or rest, or try to re-arrange delivery plans. They may also try to persuade port or terminal managers to let them enter first on terminal opening. These and other insights suggest that drivers with different goals and means should be given affordances that bring them closer to their goals. Above all, they should perceive that the holding area will afford the earliest entry to re-open container terminal. In addition, signal detection is a central aspect of control theory (Feufel and Flach, 2019), and in answering the new prompts we see that the salience of information allowing drivers to distinguish whether (i) diverting or (ii) heading directly for the closed terminal is most likely to afford punctual delivery is paramount. Such insights give a more in-depth understanding of how human actor cognitions in real situations might promote or inhibit unsafe control actions. In this way the meaning processing approach can help close the gap between identification of unsafe control actions and design of measures to help avoid them.

Table 3. Prompts analysts can use to consider scenarios explaining why humans could act unsafely (left column); illustrated with information triggered by considering the action "Truck driver drives to terminal that is closed or about to close".

Prompt	Why drivers would drive to closed terminal: Insight
How does satisfying affect ecological search and representation of affordances?	Drivers have delivery deadlines and activities planned and emerging before and after delivery; they will attempt to reduce goal discrepancy by actively seeking out ways to deliver as quickly as possible. They may not attend to re-routing signs because: they are operating in skill-based mode (fail to observe road signs as driven this way many times before); they "act to perceive" the terminal entrance (main affordance) for themselves; re-routing signs have been wrong in the past; they believe terminal managers will let their delivery in; they are not aware of costs or negative affordances e.g. they will increase delays for themselves and others.
How does specifying affect: (i) availability and use of affordances? (ii) goal-related information?	In absence of other goals, drivers will search for affordances that allow them to satisfy delivery goals e.g. open roads to terminal entrance, messages from other drivers (saying terminal still open, possible to wait on roads), heavy traffic at holding area, difficulties in turning large vehicle (effectivity). They may oversee or miss affordances that allow them to satisfy goals they are not interested in satisfying e.g. services.
How does affording influence representation of the system and goal achievement?	As long as use of open roads leading to terminals aligns with perspicacity and expected ecological structure, the system will be represented as one in which is bringing driver is closer to goal (positive effects of affordances).
Are there several goals the person wants to satisfy? How are competing goal discrepancies traded off?	Safe driving, pleasing managers, resting or refreshing, sleeping, need to get home etc.? Drivers may also need to deliver to comply with driving hours legislation.
Which goals and goal discrepancies is the person aware of (or not aware of)? (Includes consideration of designer vs. operator goals.)	Port management may assume driver goals are to deliver in compliance with diversions.
How does the person's emotional or physiological state affect how goals are attended to?	Important to consider that drivers may be in need of rest, or concerned about knock-on effects of not delivering.
Are decisions about intentions predominantly: skill-based (was a familiar action attempted when not appropriate?); rule-based (which rules were applied?); or knowledge-based (what mental model of system or process?)	Driver may deliver in skill-based mode, not attending to diversions; driver may believe (from others or past experience) that the quickest way to deliver is to ignore diversions (rules); or may simulate way to deal with scenarios in which they are turned round for not complying with re-routing signs (knowledge-based).
As they attempt to move closer to goals, what affordances would the operator want to try out?	Contact colleagues and managers to inform or be informed; try out open roads leading to terminals; stop on way to port to eat or rest; try to re-arrange delivery plans; try to persuade port managers or terminal to let them enter first on terminal opening.
What are the costs of: (i) Suboptimal use of affordances? (ii) Use of goal-mismatched affordances? (iii) Use of poorly designed affordances?	The driver may not see any costs of using open roads leading to closed terminals; may perceive and/or experience costs of diverting to holding area.
How can personal and ecological factors (interact to) affect representation (e.g. physiological factors, experience, "ecological structure", situational complexity, physical conditions)	Driver does not understand re-routing signs; driver may not be familiar with holding area and not want to use it; driver may be overloaded; poor weather may cause delays making driver think terminal may have re-opened.
What goal-related signals are salient?	Not clear whether information about costs or benefits of diverting most salient for drivers. Related to the container delivery goal, the most effective "field of safe travel" on road to closed terminal will be salient.
Which process mindsets are likely?	If I drive a little faster, I could enter the terminal before closure The quickest way to enter re-open terminal is to re-route vs. ignore diversions
What ideas are there about intentions and actions of other people and technology?	Intentions of colleagues (other drivers may try to jump the queue) Intentions of managers, police, inspectors (Port managers don't care if we wait outside the closed terminal) Intentions of employer

DISCUSSION

Preliminary analysis suggests that supplementing France's (2017) STPA extension with Flach & Voorhorst's (2020) meaning processing approach to human cognition can deepen understanding and give new insight into scenarios explaining why humans would act "unsafely" potentially causing system loss. Not surprisingly, given common methodological foundations, such as skills-rules-knowledge modes of cognition (Rasmussen, 1983), the Recognition-Primed Decision Making model (Klein, 2017), and control theory (Jagacinski and Flach, 2009), there is overlap between the prompts and questions the analyst should consider using France's (2017) "human extension" to STPA and the Flach & Voorhorst's (2020) meaning processing approach to human cognition. Nevertheless, the meaning process approach causes the analyst to deliberate on additional important aspects of control that are unique to humans. For example, it highlights that human "controllers":

- Will engage in dynamic control of the situation to stay as close as possible to goal achievement (e.g. deliver a container), and in doing so may act to perceive (e.g. drive to a closed terminal to see if it has opened) as well as perceive to act (e.g. see signs and follow diversions)
- Do not perceive a "controlled process" but the meaning (goal relevance) and value (positive or negative) of affordances
- Perception and action depend on how the surrounding ecology is represented; perception and action emerge from interactions with the ecology
- The use and effect of affordances depends on whether they capture the awareness of the person (depends both on ecological structure and on meaning and value of affordance to the person) and how effectively the person can use them
- The person will rarely perceive data from sensors alone, but interpret a dynamic array of information in the ecology, which they will relate to one or more goals
- The person will often have several personal and professional goals, and action can move the person towards (gains) or away (costs) from each goal

Once unsafe control actions are identified using STPA, the meaning processing approach can bring the analyst closer to design solutions, because of its emphasis on ecological psychology. For example, by asking about which affordance alternatives are available to the human controller, rather than which action alternatives, ideas are generated that have direct relevance for design during the analysis.

While the insights we have generated in this article illustrate the approach, they only address the control-related cognitions and actions of a single actor (the truck driver). But the meaning processing approach could be applied to several human actors in a system – preferably using knowledge elicitation techniques from naturalistic decision-making – such that problems that emerge from interactions among actors can be understood. We hope to try this out in future projects, in which we will also test the new prompts using knowledge elicitation techniques with drivers or other human controllers.

One drawback of extending the STPA approach as we describe, however, is the extra resource and understanding required. Indeed, an important aim of France's (2017) model was to provide engineers with a simple account of human control that would not require in-depth understanding of psychology; and the use of the meaning processing approach would not seem in line with this aim. While it may be possible to simplify the meaning processing approach, we ask whether engineers should attempt to understand people using a superficial approach, given that people are inordinately more complex and difficult to understand than the technology used in contemporary systems.

IMPACT

Based on preliminary analyses, we believe that the meaning processing approach to cognition could be used to obtain a less piecemeal understanding of driver behavior, one that leads to more complete and satisfying sociotechnical solutions to traffic management and other control challenges. The meaning processing approach can be used to develop solutions that better account for adaptive human control, and to recommend supplementary analyses for STPA practitioners.

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