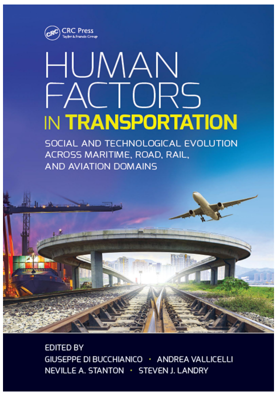

Human Factors in Transportation
Social and Technological Evolution Across Maritime, Road, Rail, and Aviation Domains

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Assessing the Fitness of Information Supply and Demand during User Interface Design

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2

Assessing the Fitness of Information Supply and Demand during User Interface Design

Christian Denker, Florian Fortmann, Marie-Christin Ostendorp, and Axel Hahn

CONTENTS

2.1 Background and Driving Forces

Accident reports reveal that human error is the number one cause of accidents in transportation. For example, a review of accidents in the aeronautical domain states that 71% of the flight accidents investigated by the U.S. National Transportation Safety Board (NTSB) between 1989 and 1992 were caused by human error (Jones and Endsley, 1996). Further, a review of accidents in the maritime domain, which was performed on the basis of data from the U.K. Marine Accident Investigation Branch (MAIB), the Transportation Safety Board of Canada (TSBC), and the Australian Transport Safety Bureau (ATSB), showed that more than 82% of accidents in shipping were associated with human error, and in 46% human error was even the main cause (Baker and McCafferty, 2005) of which 71% were caused by degraded situation awareness (SA) (Hetherington et al., 2006).

SA can be seen as a state of mind, which contributes essentially to the human decision-making process. According to Endsley's very common SA model, SA is composed of three levels: the perception (level 1), comprehension (level 2), and projection (level 3) of information (Endsley, 1995). Reports from human factors research show that 60%–77% of SA-induced errors were errors on level 1, besides 20%–30% on level 2, and 3%–9% on level 3 (Grech et al., 2002; Jones and Endsley, 1996). Thus, errors related to the perception of information are clearly the most frequent source of error within this three-level taxonomy. Furthermore, errors on level 1 can cascade to errors on level 2 and level 3 (Endsley, 1995). This implies that the elimination of level 1 errors could lead to a significant reduction of accidents and an increase of overall safety in the maritime domain.

Level 1 errors can have various causes, which cannot be strictly attributed to humans but is a severe problem with regard to information distribution and human–machine interaction on board which is closely related to the ICT (information and communication technologies) pervasiveness scenario. This can also be reasoned from the SA error taxonomy which states five causes for level 1 error (Jones and Endsley, 1996): "data is not available," "data is hard to discriminate or detect," "monitoring or observation of data failed," "misperception of data occurred," and "memory loss."

In this chapter, we focus on the two level 1 error causes "data is not available" and "data is hard to discriminate or detect." We present a formal method for the assessment of the fitness between information supplied by a user interface (UI) and the information demanded by a user. We implemented the method in an integrated systems modeling environment. We demonstrate the method with a course change task on a ship bridge. We performed an interview with system engineers from the maritime domain and a human factors ergonomist as an initial evaluation. Overall, the feedback was very positive and warrants further investigation of the method.

2.2 Related Work

In computer science formal verification methods from mathematics are used to prove the correctness of an algorithm in accordance to a defined system specification or property description. A common method is model checking. Model checking allows us to verify whether a given system model fulfills a specification. As Meolic et al. state the "method requires that a system is given with a graph, which describes the system behavior in terms of states and actions" (Meolic et al., 2000). The specification is expressed as logical propositions. The verification is done by checking the system models compliance to the propositions (Clarke et al., 1999; Meolic et al., 2000). In terms of model checking, human and machine could be defined as individual system models. In our approach the human's demand for information can be defined as the required specification. The information demand specification is used to verify the existence of the machine's information supply. Therefore, the states of the machines model contain supplied information as properties.

To establish SA and incorporate new information humans search for required information in their environment. They interact with machines and other humans to exchange information during task execution. Koreimann defined three types of information exchange between human and machine in information systems: dialog, report, and information retrieval (Koreimann, 2000). A dialog describes a bidirectional information exchange, for example, in a request and response pattern. The report is a unidirectional flow where information is transferred from a computer to the user or from the user to the computer (e.g., displaying information about the system status). An information retrieval is also a unidirectional flow, but it differs in the direction of the information flow, since information is taken from one of the information system's parts (e.g., looking for information on computer's display). The concepts of dialog, report, and information retrieval are abstractly used in our model to describe the direction of an information flow and set the initiator of an information exchange.

Besides the concrete interaction, a human has to set herself/himself into a position in which it is possible to take part in the information exchange. Here, the spatial distribution of information supply is important; because it influences the time it takes to build up SA. In the domain of human factors there exist a variety of methods considering the spatial distribution of information. One example is a method called link analysis (Chapanis, 1965; Wilson and Corlett, 2010). Link analysis allows identifying "links" between interface components (or functions) and human operators. The "links" are constructed out of a human's gaze movements between the components or a sequence of use of components or functions (Stanton and Young, 1999). For instance, the sequence of pressing button *A* and afterwards pressing button *B* would construct a link between buttons *A* and *B*. The analyst records the frequency and execution times of the links during a task under investigation. Based on the records the links are drawn onto a schematic representation of the interface to construct the so-called link diagram and a link table is created, which contains the same information in tabular form. The results of a link analysis are used to optimize the interface by reducing the spatial distance between linked components (Stanton and Young, 1999).

2.3 Information Gap Model

A concept which encompasses our view on level 1 errors is the so-called information gap introduced by Endsley and Jones (Endsley, 2000; Endsley and Jones, 2011). Their concept describes the information gap as an inconsistency between data produced and information needed. There are various definitions and meanings on what data and what information are and how they differ. The data–information–knowledge–wisdom discussion gives an insight into that field (Fricke, 2008; Rowley, 2007). Since we follow a human's task-oriented perspective, we solely focus on information. The reason is that data "has no meaning or value because it is without context and interpretation" (Rowley, 2007). In contrast, information has a format, is structured and organized, has a meaning, and a value feature (Rowley, 2007). Since information has a meaning and value feature, we will use the term "supplied information" instead of "produced data" in the remainder of this paper. Furthermore, we use the term "information demand" instead of information need.

During task execution in transportation systems, humans and machines are demanding and supplying information. This basic concept of supply and demand facilitated in our approach is taken from business studies. In business studies' controlling for instance a set theoretical concept of information supply, demand, and requirements exists (Weber and Schäffer, 2006). Within that concept information requirements describe all information which are necessary to the management, for example, for making a decision. An information demand is issued to fulfill the management's information requirements. The information demand describes information which is requested from the information supply. In the "ideal situation" the sets of required information, demanded information, and supplied information overlap (Weber and Schäffer, 2006). We used the basics of this concept and transferred it to investigate gaps between information supply and demand between humans and machines. The result is the information gap model (Figure 2.1). In the model an information gap is defined by the two complements of the intersection of information supply and demand. This means that an information gap can have two

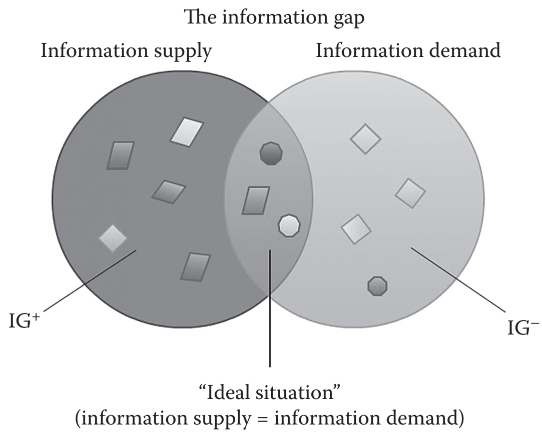

FIGURE 2.1
The information gap model describes the relation between information supply and demand. We model information supply and demand as two sets of atomic IE. IG^+ represents the subset of oversupply and IG^- the subset of undersupply of IE. In the ideal situation, information supply and demand are well-balanced.

characteristics: (1) supplied information is not demanded or (2) demanded information is not supplied. The former is also part of the previously stated definition of the information gap by Endsley. We call this part information gap$^+$ (IG^+), since there is more information available than demanded. The second part is called information gap$^-$ (IG^-), because there is less information available than demanded. This information gap definition is the baseline of our concept. In the ideal case, information supply and demand are well-balanced.

2.4 Method

In this section we present our method to detect information gaps and assess the fitness of information supply and demand during the UI design phase. The method consists of the four steps *definition*, *modeling*, *detection,* and *assessment* of information gaps and can be integrated into system design processes, such as the human-centered design process (ISO9241-210, 2009). In the following sections, we describe each step of the method in detail.

2.4.1 Step 1: Definition of Human Tasks and Machines under Investigation

In the first step of the method, the scope of the system investigation is defined. This means that the human tasks and the UI to consider are specified in detail. Therefore, hierarchical task analyses (HTA) of the humans' tasks can be conducted. An HTA typically results in a hierarchical tree-structure, where the task is decomposed into multiple subtasks (Hollnagel, 2003). Based on the HTA, atomic information elements (IEs) are extracted. IEs represent the smallest unit of information within a task which provides a meaning to the human. A digital speedometer for instance typically contains an IE (information element) that can be called "current_speed." In this approach the sufficient grade of detail is reached, when all IEs, which are necessary to complete the task at hand, are identified.

Separated from conducting the HTA, the UI is analyzed to gather the contained IEs. Contained IEs are in this case only relating to information which is shown to the users in one modus of the UI. In some cases the UI's size may exhaust the effort for gathering all IEs. Then, depending on the tasks under investigation, the grade of effort can be scaled by neglecting parts of the UI in the analysis, which would not influence the perception and SA of the humans.

During human task and machine modus definition, the analyst has to mind safety aspects. Missing or disregarding safety-relevant tasks and corresponding IEs can have a huge impact on system safety. During task definition questions like "what can go wrong?" and "which evasive tasks need to be executed?" must be considered to derive safety-relevant IEs. Another point referring to IEs is that they may be integrated with other IEs so that a new IE is derived. IEs extracted from HTAs may be integrated. By using integrated IE during modeling also parts of level 2 or level 3 SA will become the subject of the assessment's result. For instance the speedometer could be used in two different tasks to demand both the IE "current_speed" and also the IE "target_speed_deviation" as integration of, for example, "target_speed" and "current_speed." In such a case the analyst can determine whether his machine can support other SA level. The integration of IEs can be considered in modeling and in the detection and assessment of the information gap. In the remainder of the concept description, level 1 SA is considered.

2.4.2 Step 2: Modeling of Human Tasks and Machine States

In the second step, the information is gathered and an information supply and demand model (ISDM) is instantiated. The ISDM is a set of classes, which allows detecting information gaps both in a static comparison of IE sets and in a dynamic simulation of task execution. The class *InformationElement* represents an IE and is the smallest and atomic entity of the ISDM. Every IE is unique and distinct from other IEs. An *InformationElementPool* (IEP) is a global container for all unique IEs, which holds both the human tasks' and the machines' IEs. There further exist three roles (*InformationRole*) called *InformationSupplier*, *InformationDemander*, and *InformationHybrid*. An *InformationSupplier* is a role, which is capable of emitting/supplying IEs via a so-called *InformationSupplySide*. For example the whole machine under investigation can have the role of an *InformationSupplier*. The *InformationSupplySide* would then be, for example, a console or display. *InformationDemander* is a role which is capable of receiving/demanding IEs from *InformationSupplier*'s *InformationSupplySide*s. The source of an information demand is an *InformationDemandSide*, which is part of the *InformationDemander*. To enable for dynamic analysis, the *InformationDemander*s' *InformationDemandSides* and *InformationSupplier*s' *InformationSupplySide*s are ordered according to their temporal execution of demand and supply. Referenced IEs of both *InformationMarketSide*s can be ordered in the same manner, to reflect, for example, detailed sequences of eye movements (saccades). The *InformationHybrid* is a combination of both *InformationSupplier* and *InformationDemander* and can thus contain *InformationSupplySide*s and *InformationDemandSide*s. Both the *InformationDemandSide* and the *InformationSupplySide* have a location in the system under analysis. Furthermore, the *InformationMarketSide*s can be enriched with properties corresponding to their contained IEs. For example a value of importance or a value representing the saliency of IEs could be defined for each IE. This enables not only for spatial analysis of the human–machine interaction, but also allows considering further human or machine factors in the later analysis. An *InformationFlow* is used to connect the *InformationDemandSide*s with *InformationSupplySide*s. This concept allows modeling the fulfillment of information demand via distributed *InformationSupplySide*s. The *InformationFlow* class can be used to model dialogs, reports, and information retrievals. With the model it is also possible to express information which is not perceivable on the UI, but existing in the internal model of the human or machine. The class representing this is called *InformationPotential*. In case of a machine this class can contain, for example, information produced by sensors, which are currently not showing on the display. For humans the *InformationPotential* can contain all IE which were already perceived during a task's execution. The construct can also be used to model cognitive limitations, for example, to set a max amount of information in a human's memory. The *InformationPotential* can increase or decrease in the amount of contained IEs during task execution.

2.4.3 Step 3: Detection of Information Gaps

In the third step information, gaps are detected by analyzing the ISDM. Therefore, information supply and demand is compared to check for existence of IG^+ and IG^- in the system under investigation. The comparison of the properties of the *InformationMarketSide*s is also a part of the detection. As preparation to the detection and assessment, the *InformationDemander*s' *InformationDemandSide*s are inspected. For each *InformationDemandSide* connected *InformationSupplySide*s are resolved, which are connected via *InformationFlow*s. The *InformationSupplySide*s' IEs are then aggregated to form a joint set of supplied IEs. IEs of the focused *InformationDemandSide* are considered as a set of IEs as well. Of course properties of the *InformationDemandSide* and *InformationSupplySide*, which have been previously annotated, need to be referenced to their corresponding IEs, if they have to be considered in the analysis as well. A possibility for annotating the sets is to construct tuples, which consist of the IE and its properties.

Having the two sets of information supply and information demand set up, the detection of the information gap may begin. Let A be the information supply set and B be the information demand set, then $f(A - B)$ results in IG^+ and $f(B - A)$ results in IG^-. The function f is called the matching function. It maps the referenced IEs of sets A and B to each other. The function allows scoring differences in properties of IEs between both demand and supply side. The results of the detection step are the sets of IG^+ and IG^- including properties' scores.

2.4.4 Step 4: Assessment of Information Gaps

In the fourth step, the information gaps are assessed. The assessment is based on the two sets A and B and their properties which were created in the third step. The assessment is done by application of Tversky's ratio model similarity (Tversky, 1977)

$$S(a,b) = \frac{f(A \cap B)}{(f(A \cap B) + \alpha f(A - B) + \beta f(B - A))}, \quad \alpha, \beta \geq 0 \tag{2.1}$$

It is a mathematical model which allows comparing two sets and results in a ratio. The ratio indicates the similarity of the given sets A and B and expresses it as normalized real number between 0 and 1. Here again, the complements of the intersection of A and B represent the information gap consisting of IG^+ and IG^-. α and β are weightings to the complements and hence allow for changes of the influences of IG^+ and IG^- to the metric's result. When $\alpha = \beta = 1$ the model reduces to $f(A \cap B)/f(A \cup B)$ (Gregson, 1975). Again, the function f is called the matching function. The matching function allows to integrate further mapping functions between both *InformationDemandSides'* and *InformationSupplySides'* IE-referencing properties. The implementation of the matching function depends on the particular property and its metric. A simple example is the mapping of an IE's value of importance for the *InformationDemandSide*.

When calculations for each *InformationDemandSide* were carried out, the arithmetic mean is used to rate the entire tasks in relation to the machines. When the metric result equals one, no information gap exists. A result of zero would indicate that there exists no information exchange. Instead of the arithmetic mean, it is of course also possible to apply other, even more complex functions, which weight in a more meaningful manner, for example, in accordance to task priority.

2.5 Implementation in a Modeling Environment

In this section, the implementation of the concept is described. The aim of the implementation is to show how the concept can be integrated into existing integrated modeling environments to automate the static detection and assessment method. We chose to implement the concept as plugin to MagicDraw. The UML (unified modeling language) tool supports business process, architecture, software, and system modeling (NoMagic, 2014). The main advantage is its extensibility via the provided OpenAPI. The OpenAPI allows access to various internal modeling constructs and enables us to extend MagicDraw with custom plugins. The internal models are mapped to the ISDM and a plugin is developed which enables us to detect and assess information gaps. The static analysis disregards spatio-temporal aspects of the information gap. An IE property which states the priority within a task under investigation is integrated into the assessment.

2.5.1 Mapping the ISDM

The ISDM is mapped to existing constructs of MagicDraw. These constructs are SysML requirement diagrams, UI models, and traceability links. In systems engineering SysML requirement, diagrams are used to define requirements to a system and requirements' relations (Weilkiens, 2011). Here, the SysML requirement diagram is used to express the *InformationDemander* with one *InformationDemandSide* of the ISDM. The diagram's parts called "information requirements" represent IEs. The priority of an IE is settable via the information requirement's property attribute. UI models, which can be created with MagicDraw's UI Modeler, are used to constitute the *InformationSupplier* including one *InformationSupplySide*. Traceability links enable to connect SysML requirement diagram's information requirements with the UI model's elements and therefore surrogate the *InformationFlow*. *InformationElementPool*, *InformationPotential*, and *InformationHybrid* are not considered in this implementation.

2.5.2 Plugin Implementation

The requirement diagram, UI model, and traceability links are facilitated by the developed plugin extension. The plugin is implemented in Java and consists of the two classes

IGMetricPlugin and *IGMetric*. These extend the abstract classes *Plugin* and *Metric* of the MagicDraw OpenAPI. The *IGMetricPlugin* instantiates *IGMetric* in its *init*-method and adds it to the *MetricsManager* of MagicDraw. This makes the metric available in MagicDraw. The *IGMetric* contains the logic for the automated detection and assessment. In its *calculateLocalMetricValue*-method, the ratio model similarity is calculated. During calculation IEs of the information requirements diagram are mapped to the priority. The result of the calculation is shown as a report in MagicDraw. The report states IG^+, IG^-, IEs of the "ideal situation," and the result of the ratio model similarity calculation. The method *acceptModelElement* is used to specify permitted input elements to the metric. Here all required diagram elements are permitted. An example of the results is presented within the use case in the next section. As completion of the implementation, the plugin was added to MagicDraw.

2.6 Use Case

We applied our method to assess the fitness between an autopilot UI (defines the information supply) and a course change task on a ship (defines the information demand). The course change task under investigation is artificial, since it only focuses on operational changes to keep the ship on its track and is not capable of extraction of all required information. For instance, in such a task a target course is identified through other nautical means, which are not considered in this use case.

The course change task was examined in a HTA which was conducted and evaluated in an expert interview with a master-licensed seafarer. The resulting HTA is shown in Figure 2.2 and was used to identify the IEs demanded during the task. To change the course, the autopilot needs to be configured, before maneuver execution is possible. A maneuver is executed by setting a new heading to the autopilot and monitoring the ship's corresponding behavior. The identified IEs were added to a requirement diagram in MagicDraw (see Figure 2.2). The diagram contains nine IEs called *current_rate_of_turn*, *new_rate_of_turn*, *current_rudder_limit*, *new_rudder_limit*, *current_heading*, *new_heading*, *current_reference_compass*, *new_reference_compass*, and *current_rudder_position*. Every IE got a priority of 1 assigned. Exceptions to this are the IEs *current_heading* and *new_heading*, which got a priority of 2 assigned, only for demonstrative purposes. Next, a commercial autopilot's UI was recreated in an abstract manner with MagicDraw's UI modeler. The abstract UI model of the autopilot is shown in Figure 2.2 as well. There IEs of the UI model are represented as *GroupBoxes* and a variety of control buttons were aggregated to *GroupBoxes* called "controls" to minimize the textual output of the plugin. This of course influences the metric's result. The *GroupBoxes* were then linked to the information requirements with MagicDraw's traceability functionality. Finally, the *IGMetric* was executed to calculate the ratio model similarity between the information supply and the information demand. The textual output containing IG^+, IG^-, and the ratio model similarity's result is shown in Table 2.1.

One information requirement, or IE respectively, was not implemented in the UI model (IG^-) and seven supplied IEs were not demanded within the task (IG^+). The ratio model similarity results in 0.578947. This results from the mapping function to the information requirements' priority property. In fractional notation, the result equals $(11/(11 + 7 + 1))$.

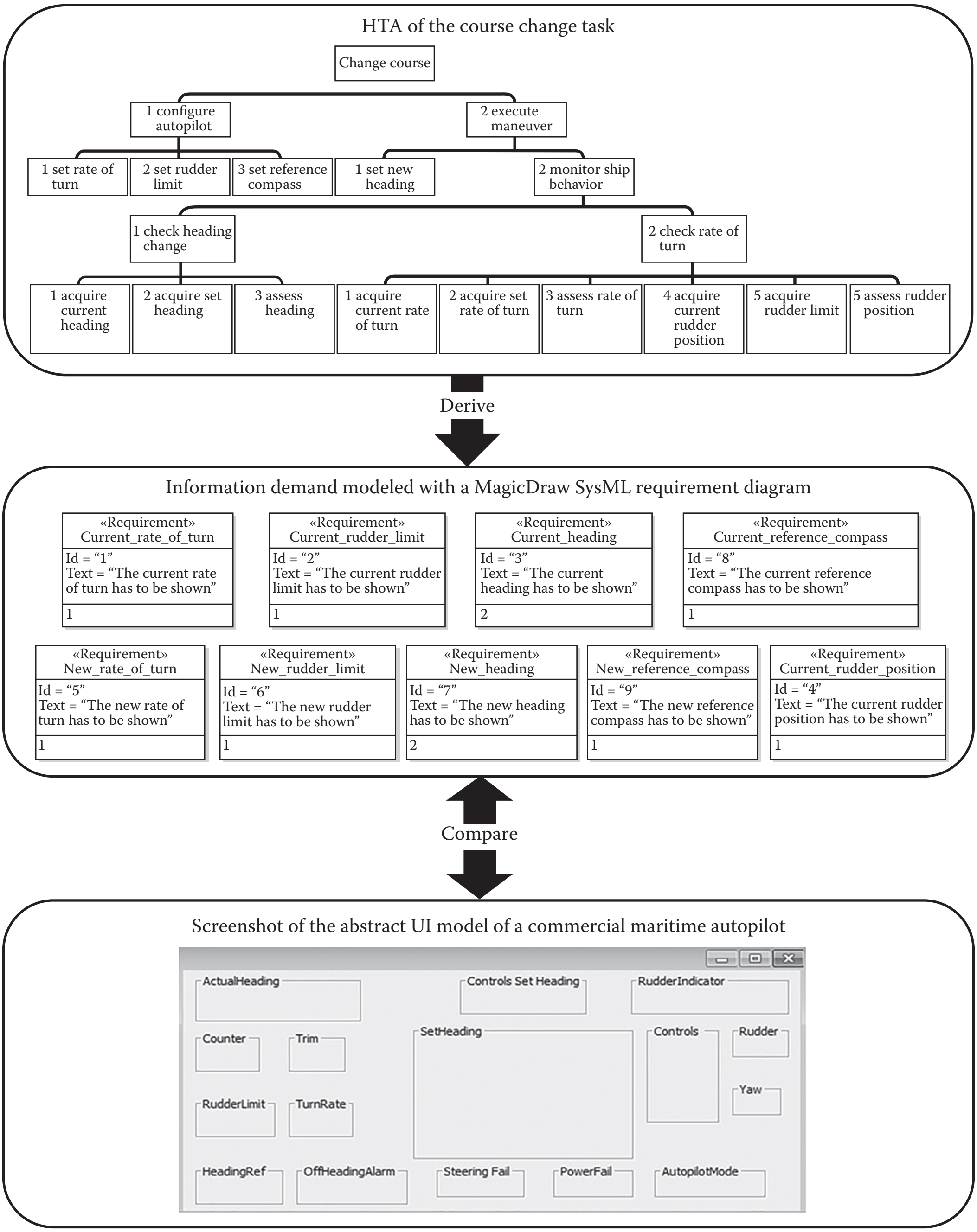

FIGURE 2.2
Overview on derivation of information requirements from HTA and comparison to the abstract UI model of a commercial maritime autopilot.

TABLE 2.1

Calculation Results of the Information Gap Metric Plugin

WARNING (IG^-): Requirement current_rate_of_turn is disregarded in GUI!
WARNING (IG^+): GroupBox AutopilotMode is not derived from information requirement
WARNING (IG^+): GroupBox Yaw is not derived from information requirement
WARNING (IG^+): GroupBox PowerFail is not derived from information requirement
WARNING (IG^+): GroupBox Steering Fail is not derived from information requirement
WARNING (IG^+): GroupBox Controls is not derived from information requirement
WARNING (IG^+): GroupBox Counter is not derived from information requirement
WARNING (IG^+): GroupBox Trim is not derived from information requirement
Ratio model similarity: 0.578947

2.7 Evaluation

We evaluated our approach in collaboration with system engineers from the maritime domain and with a human factors ergonomist. Therefore we presented the concept of the method to them and demonstrated its application. Then we asked the experts to estimate the applicability, benefits, and shortcomings of the method. Overall, the feedback was positive. The experts found that the method is a good complement for system design processes. Especially the seamless integration into an existing systems engineering tool was stated as beneficial. The experts agreed that the spatiotemporal resolution of the information gap needs to be addressed in future work. Furthermore, the ratio model similarity metric delivering a normalized estimation of the severity of information gaps was considered as helpful. They estimated the metric would have its strength in the assessment for comparison of various UIs and different UI modes during design time. An engineer mentioned that the approach requires a huge initial modeling effort and that detailed task analyses may consume much time. During development this can have a negative bias for the time to market. However, another expert with background in task analysis reasoned that gathering IEs would cause little additional effort to a typical task analysis. In the end a comparison of cost and benefits will drive the decision on whether to invest in additional modeling effort. The discussion with the experts expressed the need for further studies which examine the costs and benefits. Another point in the discussion concerned the way in which IEs are supplied. For instance information presentation capabilities were not regarded in our use case, but have an impact on how information is demanded. The experts claimed that the integration of a rating for information presentation capabilities would be of interest as an extension to the presented approach. Such a rating could be integrated into the *InformationMarketSide*s and the mapping function of the ratio model similarity calculation.

2.8 Conclusion and Outlook

In this chapter, we have demonstrated a method to assess the fitness of information supply and demand on the UI during the design phase to improve the information distribution and thereby the human–machine interaction on board with regard to the ICT pervasiveness scenario. As basis of our method, we derived the information gap model comprising information supply and information demand. Our method consists of the four steps: (1) definition of human tasks and machines under investigation, (2) modeling of human tasks and machine states, (3) detection of information gaps, and (4) assessment of information gaps. We applied the method to assess the fitness of information supply and demand of an autopilot component in a course change task on a ship bridge. We presented our method and its application to system engineers and a human factors ergonomist. Then, we interviewed them to get an initial evaluation. In the interview, we asked the experts to estimate the applicability, benefits, and costs of the method.

The overall result is positive and warrants further research. A study which investigates the applicability of the method with respect to benefits and costs would be of interest for industrial stakeholders. Another research demand concerns the extension of our method by including further properties and the investigation of distributed information supply and demand. In our implementation we considered an IE's priority out of the demand side's perspective. As extension to this work, further properties of IEs which influence the information flow between information supply and information demand side could be considered. For instance an integration of the properties of Wickens' SEEV-Model (salience, effort, expectancy, and value) from applied attention theory may be considered (Wickens and McCarley, 2008). In future work, the effort property of this framework can be used to compensate for the spatiotemporal aspects which are not considered within our implementation. Furthermore, we conclude that analysts have to consider IG^+ and IG^- during assessment with the presented implementation, since the arithmetic mean of multiple ratio model similarity metrics may mask important information gaps. However, our method enables us to integrate more powerful aggregation functions, which may compensate that shortcoming. We further identified that the presentation of the assessments' results could be improved. Analysts applying our implementation to optimize complex systems consisting of multiple humans and machines might struggle in finding major system problems in the overloaded textual results. The results could be improved through visualization, for example, as a graph visualization (Herman, 2000).

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