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Classifying conceptual models applied to develop an autonomous snow-plowing system

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Abstract. The integration of autonomous systems is increasing, while the development of future systems faces a growing complexity in their interactions with human operators. Conceptual modeling helps simplify the complexity while also being realistic enough to make sense. This paper demonstrates how a small company that develops an autonomous system for snow plowing machines at airports applies various conceptual models. The paper has classified the conceptual models according to A3AO, CAFCR+, and TOP frameworks with a Human Systems Integration perspective. Findings suggest that a mixed modeling approach with viewpoint hopping is used and found effective during the development of human and autonomous collaboration systems for confined industrial environments.

Introduction

Autonomous systems with human collaboration increase the level of system complexity. The increasing complexity demands comprehensive insight into the socio-technical aspects when developing such systems (Behymer & Flach, 2016). The socio-technical system encompasses the human system, the technical system, its components, and its dynamic interactions with the environment.

We investigate how developing an autonomous system with human and technical collaboration encompasses various system aspects and perspectives kept during product development. We conducted this case study within a small Norwegian entity of 27 employees, henceforth called the Company. The main product is an autonomy service platform that can be integrated into new and existing industrial environments. This research focuses on the development of autonomous runway sweepers for removing snow at airports while maintaining safety and operational integrity. The Company is responsible for the autonomous technology and IT systems. The Company supports five to seven unmanned sweepers in the closed airport environment with a lead safety driver in front. Each snow-plowing mission is proposed beforehand with the aid of a Planning Tool. In the Planning Tool, they plot the route by selecting paths and authorization points. Additionally, adjustments can be made during mission execution. Most snow removal tasks can be unmanned, but some inconveniences demand human intervention. Even though an airport is a controlled environment, several dynamic variables make the system of systems complex, such as dynamic factors, for instance, air traffic, weather effects, infrastructure maintenance, and upgrades.

Lightweight architecture, such as Conceptual Modeling, helps simplify the complexity to aid the modeler in understanding, reasoning, communicating, and making decisions with while also being realistic enough to make sense (Langen, Muller, et al., 2023; Muller, 2015). Conceptual models are a mixture of formality and natural language expressions. In other words, Conceptual Models and Modeling are the artifacts and process for viewing the complex real world at a humanly comprehensible level. Conceptual modeling supports the industry's systems architecture and product development process (Haveman, 2015). Additionally, we have found conceptual modeling suitable for creating manned-unmanned systems (Langen, Muller, et al., 2023). Examples of models are dynamic behavioral diagrams, like workflow, task analysis, and activity diagrams. Additionally, we have scenario and storytelling techniques such as use case and visual concept of operations, with both white box and black box views. Moreover, swimming lane diagrams with use cases showing the actions and activities of each role in a given sub-system (Alexander & Maiden, 2004; Muller, 2015). We distinguish conceptual models from first principle models, empirical models, mental models (Muller, 2021), computer models, simulation models, and the final system solution itself (Robinson, 2008).

Systems Architecting is the activity of creating based on problem, solution, and system knowledge within the human, technological, and business context. A systems architect emphasizes the use of viewpoint hopping to get holistic, various, and simultaneous perspectives of the system aspects. CAFCR+ is an open-ended architectural framework that is decomposed into six system aspect viewpoints with sub-methods and models from many disciplines (Muller, 2004). Viewpoint hopping is more useful when one has a perspective that guides through the views. A relevant perspective during the development of human-machine collaborative systems is Human System Integration (HSI). HSI should be regarded as an overarching perspective throughout the engineering process, ensuring that Technology, Organizations, and People (TOP) are considered throughout the product life cycle (Boy, 2013). A part of a systems architect's tasks is to capture, collect, and communicate data, information, and knowledge with stakeholders through the means of models (Langen, Ali, et al., 2023). The A3 Architecture Overviews (A3AO) tool highlights views relevant for knowledge capture and communication (Borches & Bonnema, 2010).

There is a need to understand the use of conceptual methods that aid in transforming the complexity to a level that various types of stakeholders can understand, reason, explore, validate, communicate, and decide on the system they are developing. We argue that during the development of complex socio-technical systems, the systems engineers need to understand the systems aspects, HSI perspectives, and have the means to communicate these perspectives with stakeholders. Therefore, we investigated the use of CAFCR+ for the systems architectural views, TOP model (Technology, Organization, People) for HSI perspectives, and the A3 Architecture Overviews (A3AO) for the representation of these perspectives.

Research Questions. To investigate how an agile small company has used Conceptual Modeling within the perspective of Human Systems Integration in their Snow Removal Systems, we ask the research question, "What conceptual models are utilized and perceived to be effective during the development of an autonomous snow-plowing system?"

Method. The research method was a case study within an industry-academic collaboration (Ali et al., 2022) from 2021 to 2023. The industry-academic collaboration had four workshops and 11 meetings, in addition to monthly research project meetings. The authors conducted five in-depth interviews with key developers in the Company, having the role of CTO and Systems Architects. Additionally, we analyzed the Company's conceptual modeling platform by going through 90 drawing boards and 493 models. The conceptual modeling platform is a lightweight digital collaboration platform that facilitates interactions, communication, and project management. These boards and models were filtered for relevance for snow-plowing systems development; thus, the final review numbers were 477 models spanned over 61 drawing boards. We address the research question by examining the conceptual models used and assessing the developers' perception of their effectiveness. For grounding the conceptual models in established Systems Engineering frameworks, the main author classified them according to CAFCR+, TOP, and A3AO.

Background Frameworks

CAFCR+. The CAFCR+ model is a structured and recursive reasoning approach to architecture that is decomposing into six views: Customer Objectives, Application, Functional, Conceptual, and Realization, plus Life Cycle (Muller, 2015). Each view addresses a specific aspect of the system, from understanding customer needs to defining technical implementation. The Customer Objectives view focuses on understanding the customer's problems and needs. The Application view bridges the gap between customer objectives and technical implementation. The Functional view captures the "what" of the product, encompassing both functional and quality requirements to ensure it meets customer expectations and is within the system's boundaries. The Conceptual view describes the "how" of the product through concrete design solutions. The Realization view builds upon the conceptual view with concrete implementation details, ensuring that the architecture may function as intended. The Life Cycle view refers to the entire span of activities a system undergoes. Key activities are those related to sales, development, production, logistics, installation, operations, maintenance, upgrades, and R&D.

TOP. The TOP framework is a model designed to consider the Technology, Organization, and People along the life cycle of a system (Boy, 2013). The TOP model evolved from human-centered design, giving useful perspectives into Human Systems Integration. Technology consists of hardware and software artifacts. Organizations are the procedures, processes, and coordination of systems. People are the stakeholders involved, such as the Planner and Operator. The socio-technical interrelationship between Technology, Organization, and People is challenging during the product development of new autonomous systems.

A3AO. A3 Architecture Overviews (A3AO) is a knowledge capture and communication tool. Toyota Motor Corporation developed it, and Daniel Borches refined it (Borches & Bonnema, 2010). It employs a standard A3-sized sheet to communicate architectural information using a combination of text and diagrams. A3AO is brief, supports multi-disciplinary communication, promotes common understanding, and facilitates early validation. It can be used in various engineering domains and has been shown to be effective in product development, conceptualization, and process architecting. The essential viewpoints in A3AO are functional view, physical view, quantification view, and visual aids. The Functional view shows the functions and their flow, typically in the format of verb + noun. The Physical view depicts the hardware and software elements. The Quantification view involves numerical data of key parameters, such as measurements, experts' estimations, and best guesses. The Visual Aid views tend to be ambiguous to come closer to the mental model by employing pictures and visual representations to describe the system context and its functions (Borches & Bonnema, 2010).

Type of Conceptual Models used during product development

The following section highlights the type of models for CAFCR+ views (Muller, 2015), as seen in Figure 1, and A3AO views (Borches & Bonnema, 2010) presented in Figure 2. Additionally, the various TOP perspectives (Boy, 2013) are explained. These models are extractions from the Company.

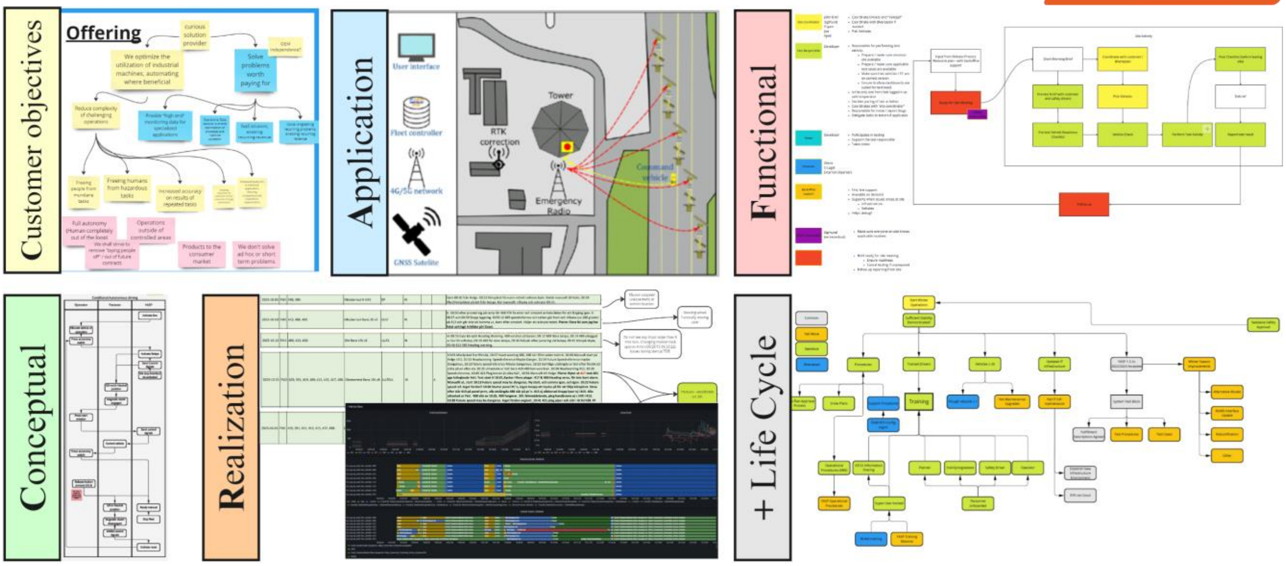

Figure 1. Representation of the models used classified according to the CAFCR+ framework

CAFCR+. The Customer objective view revolves around the business aspect of the company and customer, here showing the Key Driver decomposition within a given industry domain (see Figure 1). Some of the key drivers are having a safe and robust system, optimizing existing machinery, reducing the complexity of challenging operations and freeing humans from hazardous tasks while increasing the accuracy of repeated tasks. The Application view sets the system of interest into its context. Figure 1 Application view shows how it relates to the other systems in the environment, exemplified by a context diagram of the operational communication between the airport, snow-plowing sweepers, and the autonomy service platform. The Functional view highlights what activities are being done. Figure 1 Functional view shows tasks on the site regarding test activity, going from resource plan, morning brief, and vehicle startup to reporting the test results, to office support. Other Functional views are use case stories, external interfaces, and information flow. The Conceptual view shows how the product is working. Figure 1 Conceptual view shows a swimming lane diagram of how a conditional autonomous driving use case shall work. The swimming lane encompasses the startup activity flow between the operator, the drive-by-wire system, and the autonomous service platform. Typical conceptual view models used are decomposition and internal interfaces between sub-systems. The Realization view typically connects concepts with real-world data. Figure 1 Realization view shows a part of a four-week post-analysis of root cause failure. Other realization views are typically performance and safety analysis. The Life Cycle view, in Figure 1, shows the project's Work Breakdown Structure divided between the case company, owner, and customer regarding procedures, training, vehicles, and IT infrastructure. Another Life Cycle view frequently used was roadmaps for development planning, focusing on site implementation, front and back-end functionalities, release time, and responsibilities.

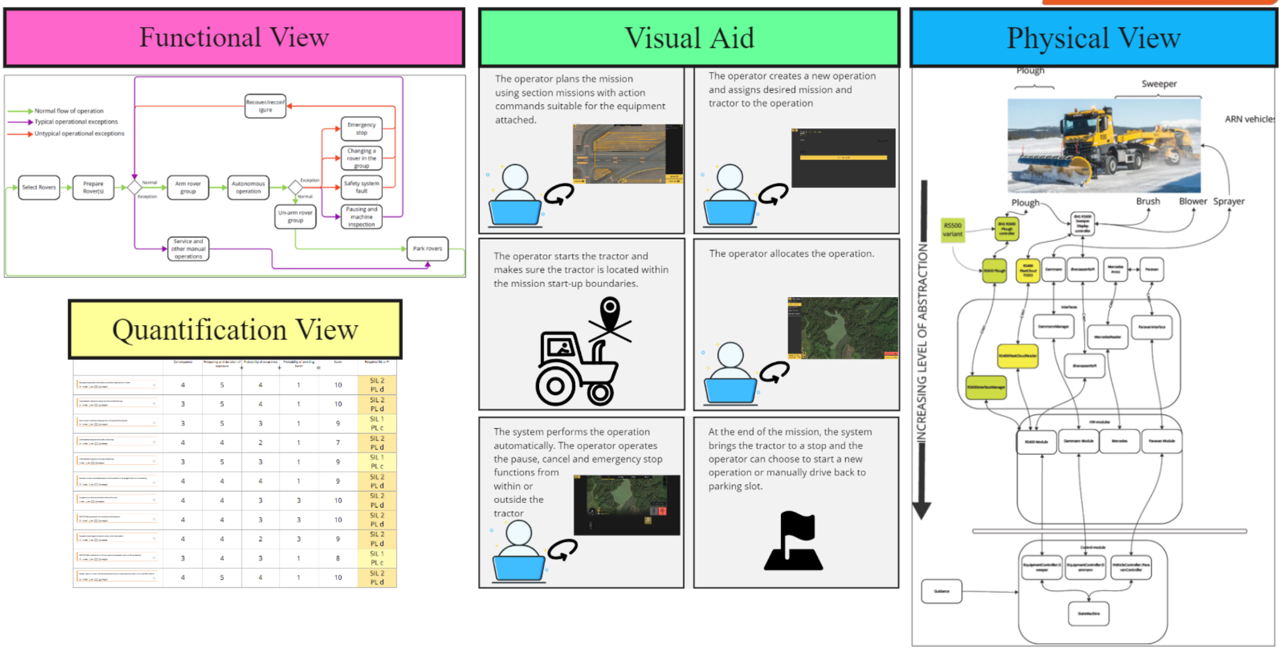

Figure 2. Representation of the models used classified according to A3AO views

A3AO. The Functional Views typically convey a flow through activity and state diagrams and other traditional diagrams seen in UML and SysML languages. Some of the Functional UML diagrams are inserted into the conceptual modeling platform. Figure 2 Functional View shows a functional flow diagram conceptualizing the normal operation, typical exceptions, and untypical exceptions. The Physical Views show the tangible entities, their relation to other objects, and where they are positioned. Physical Views are usually shown as block diagrams. In Figure 2 Physical View, we see a decomposition of the parent system (sweeper vehicle) down to the component level. The Quantification Views portray the data and information input, such as risk assessment score as seen in Figure 2, but also bug reports, failure data analysis, and operational uptime and efficiency. The Visual Aid views are the mix of models used to convey a story, such as using the graphical user interface to explain the concept of operation. The Visual aided models tend to be less refined than traditional formal models. However, they tend to collectively merge parts of functional, physical, and quantitative models to portray a new level of insight.

TOP. We looked at the type of perspectives the various models had in terms of seven TOP-views. Technology-oriented models focus solely on technological aspects, as seen in Physical View in Figure 2. Technological + Organizational model, as seen in Functional View in Figure 2, includes how the organizational procedures interact with technologies. In Organizational-oriented models, we tend to see project management models, as seen in Life Cycle view (Figure 1). Organizational + People models, as seen in Functional View (Figure 1), typically include who is doing what in a procedure. In People-oriented models, we see stakeholder diagrams and user descriptions. Technology + People models, as seen in Conceptual View (Figure 1), tend to have mock-ups of human-machine interfaces. The TOP-oriented models include all three perspectives, such as Figure 3, which shows a startup use case through an activity diagram.

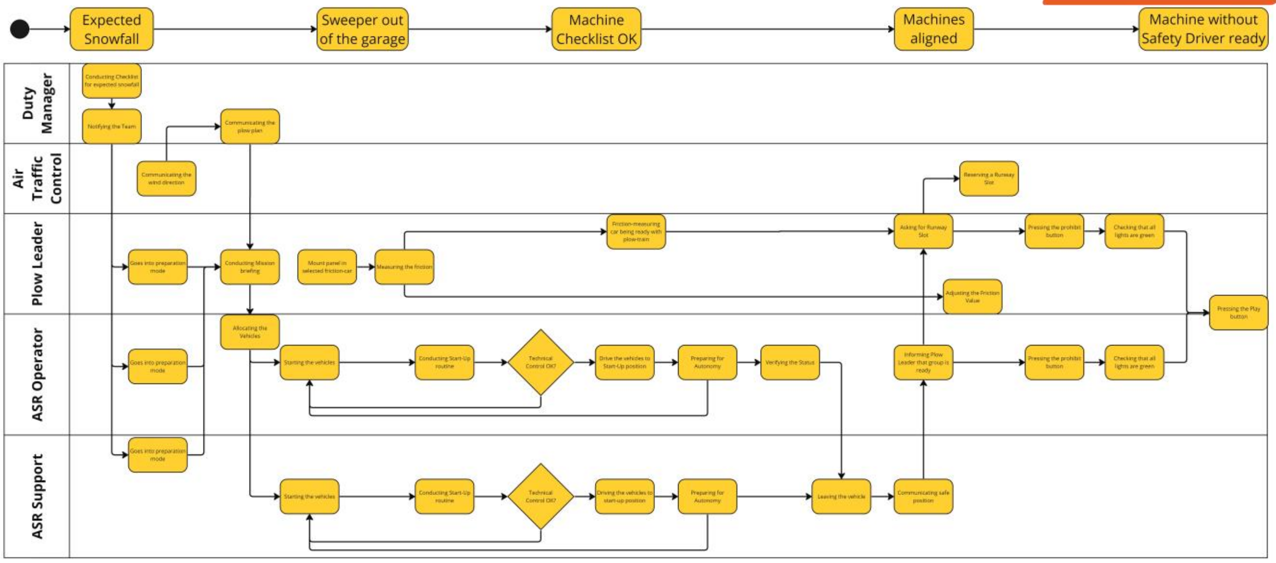

Figure 3. Results from Event Storming workshop Tasks and Roles during operational startup

Distribution of models used during autonomous system development

This section counts the number of models the case company has used to create an autonomous service platform. We classify the models into CAFCR+ and A3AO views corresponding to seven variations of TOP perspectives. Figure 4 and 5 shows the distribution of the 477 models. By dividing the total number of models into the three TOP perspectives, we see that 60 % are Technology, 21 % are Organizational, and 19 % are People.

Number of models	Customer	Application	Functional	Conceptual	Realization	Life Cycle	Total TOP
TOP	17	12	26	23	6	23	107
Technology	15	13	34	107	10	13	192
Technology & Organization	9	4	8	8	1	12	42
Organization	0	8	4	4	4	12	32
Organization & People	4	7	3	5	0	0	19
People	2	2	1	1	0	1	7
People & Technology	4	10	24	37	0	3	78
Total CAFCR+	51	56	100	185	21	64	477

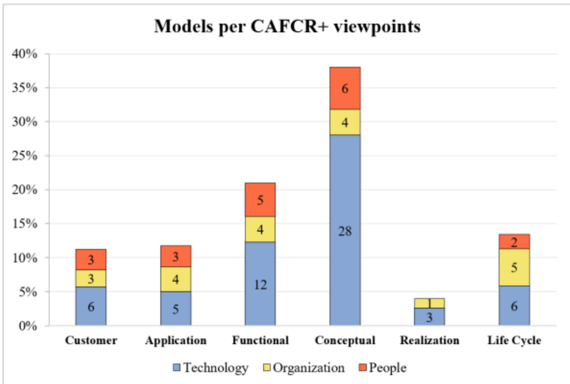

Figure 4. Amount and percentage of models classified according to CAFCR+ and TOP

CAFCR+ & TOP. Figure 4 shows the distribution among CAFCR+ and TOP in number (left) and percentage (right). The graph shows, in percentage, that most models are classified in the Conceptual (38 %), followed by the Functional (21 %), while the Realization has a low representation (4 %). The Organization and People are linear throughout the graph, ranging from 0 % to 6 %. In comparison, most views are Technology-oriented, with 28 % representation in the Conceptual view.

Number of models	Functional	Physical	Quantification	Visual Aids	Total TOP
TOP	35	13	4	55	**107**
Technology	73	70	9	40	**192**
Technology & Organization	17	10	2	13	**42**
Organization	16	5	2	9	**32**
Organization & People	5	1	0	13	**19**
People	1	1	0	5	**7**
People & Technology	35	9	0	34	**78**
Total A3AO	**182**	**109**	**17**	**169**	**477**

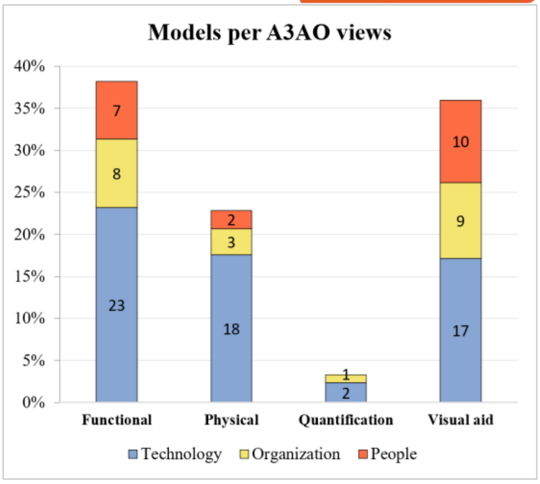

Figure 5. Amount and percentage of models classified according to A3AO and TOP

A3AO & TOP. Figure 5 shows the distribution among A3AO and TOP. The graph shows, in percentage, that most models are within the Functional category (38 %), followed by Visual Aid (36 %), while Quantification has the least representation (3 %). The Technology perspective is evenly represented between Functional (23 %), Physical (18 %), and Visual Aids (17 %) views. Organizations and People perspectives have the least representation within Physical and Quantification views.

Interview and analysis on the use of conceptual models

This section explores the interview results from five systems engineers in the Company, revealing two emerging themes: mixed modeling approach and co-creation activities.

Mixed modeling. The interview results revealed they use various modeling methodologies from systems engineering, user experience design, and the software domain. However, personal preference and the intention of the modeling define what approach is being used. Some engineers prefer to tell a story, while others prefer to have structured models. The Company does not have a defined library of best practice models that shall be used. Thus, their model selection and inspiration come from previous work, Systems Engineering Body of Knowledge (Cloutier & Hutchison, 2022), and typical models from the software domain. Typical software models are State Diagram, Performance Measurements, User Documentation, Activity Diagram, Swimming Lane, and User Stories. Specifically, from Systems Engineering, they use Roadmapping for overarching plans, and ConOps as an anchor for overall system operation. They build models in a way that they can be updated over time. The interviews showed that they find mixed modeling to be effective. Mixed models are models that are fused together from individual models, used across each other, and facilitated for receiving feedback, with plenty of iterations. Additionally, we see from the distribution of models used that 52 % have a combination of various T-O-P perspectives (n = 246), whereas 48 % of the models are purely Technological, Organizational, or People-oriented (n = 231).

On why there are few realization and quantification models, their reasoning was that the developers who did detail engineering mostly model on whiteboards followed by implementation straight into Python coding. Additionally, business managers looked at the conceptual models but did not create models themselves. Thus, Systems engineers and tech leads were the ones who actively used the conceptual modeling platform. The CTO reflected that they should have inserted more detailed engineering models into the contextual models, such as the calculation for breaking distance and snowplowing area and how this relates to the top-level requirements.

Co-Creation. Insight from the interviews revealed that the effective use of modeling is to facilitate co-creation with subject matter experts, customers, and end-users. Event Storming was a method they tested to co-create a mission startup workflow, as seen in Figure 3. The Event Storming aimed to understand the flow with input from various perspectives and identify pain points. Event Storming is a domain-driven design method where participants place activities-notes in a given scenario and later organize them into a workflow along a timeline (Brandolini, 2015). The results were that the Event Storming with customers improved shared understanding of the system and its use. The airport stakeholders had several a-ha moments, such as in the transition from manual to autonomous operations, numerous pieces needed to fall in place to resolve the complex solution. The participants received a higher level of understanding of why the transition from human to machine is challenging. For the stakeholders involved, the modeling co-creation had a positive effect in terms of clarifying all the activities that a mission startup requires. Reflection showed that the Event Storming would have been beneficial earlier in the product development.

Interviews reveal that models are not used frequently during external meetings compared to internal use. Additionally, they tend to use different types of illustrations depending on internal or external use. Typically, they simplify their conceptual models and make them at a higher abstraction level during external meetings. An example is a swimming lane diagram, where they have fewer activities and actors when presented to external stakeholders. Thus, those conceptualizations used effectively externally are illustrative and use case models as they are on a higher simplified abstraction level, which fosters discussions.

One example is how the Company has used prototyping visualization as a basis for discussions. They visualize the Human Machine Interface weekly by showing their product (Planning Tool) and wireframing. They use the prototype when simulating and discussing the use case scenarios with end-users and other subject matter experts. The interviews indicate that the Company considers this agile approach to be effective. However, a downside is that the customer and end-users get higher expectations because they see more possibilities of functionalities than what the system is planned for.

Concluding remarks

Based on a case study of a small company creating an autonomous snow-plowing system for airports, we have investigated the practical use of conceptual models by evaluating and classifying them according to CAFCR+, TOP, and A3AO frameworks. Additionally, we have gained insight into the developers' perception of the effectiveness of the conceptual models.

The number of models increases from the Customer to Application and Functional system aspects, with a peak in the Conceptual. The Conceptual, which describes the how, demands more modeling as the system moves from a higher abstraction level to detailed solutions that can be broken down into parts and lines of code. The Technology perspective is the dominant view in all of the system architectural views, as their ownership is in delivering the technical part of the autonomous solution. Organization and People perspectives have a minor but steady representation throughout the system architectural views. The Realization aspect had the lowest representation in their conceptual modeling platform because simulation and code implementation are done in dedicated software. The Company has collected technical system data and information for further data analysis, but little is represented in their conceptual models. They aimed to analyze measurements from how the Operators use the interfaces, although no Realization models contained data or deeper analysis of the People perspective (i.e., human factor data).

We can see that the case company uses a mix of formal and informal models, depending on the type of purpose or insight they need. Typical formal models include functional flow and block diagrams, while informal models typically involve visually aided representations, such as mixing the graphical user interface with the concept of operation. The traditional Functional and Physical views were frequently used, mainly to depict the Technology aspects of the system. Quantification views were the least represented in their conceptual modeling platform, especially on the People perspective. Quantification views usually remained at whiteboards and sometimes directly realized to usable codes. Interview feedback suggests they might have found value in bringing these viewpoints to the conceptual models. An example of early verification through conceptual estimate is quantifying the total breaking distance based on radio communication delay, vehicle speed, and surface friction, resulting in a specific safety distance requirement between the autonomous sweeper vehicles.

A large majority of the models are labeled as Visual Aids. In these models, we see a relatively higher degree of Organizational and People perspectives being included. This might suggest that developers prefer to use mixed models to tell a story in complex issues. Meanwhile, complicated issues are dealt with through functional, physical, and quantificational views. According to the interviews, informal models are more effective in external meetings and co-creation sessions, than traditional UML and SysML formal models. The case company highlights the importance of easy-to-use lightweight software tools, such as their conceptual modeling platform, that can be easily understood and edited. Primarily during co-creation, as it generates a higher degree of engagement. Additionally, lightweight tools have internal benefits due to easy accessibility and instant up-to-date information. However, the Systems Architects made most of the conceptual models, while developers mainly generate their own domain models within their environment, and the business managers only appreciate the shared models.

In conclusion, semi-formal models drawn in a shared lightweight conceptual modeling platform that convey the complexity through mixed modeling are useful and effective when developing autonomous systems for a confined industrial environment. The development of autonomous snow-plowing systems may see viewpoint hopping between system architectural views, using formal and informal models. In a Human Systems Integration perspective, we see in this case study that 60 % of the models had a Technology perspective, while 21 % had an Organization perspective, and 19 % had a People perspective. Considering the findings, further research can experiment with the use of, and the effect of implementing, a higher degree of People and Organizational perspectives in Visually aided conceptual models.

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