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Model-Based Systems Engineering for the Design of an Intermodal High-Speed Freight Train Terminal

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Since rail traffic is the mode of mass transport with minimal transportation-related greenhouse gas emissions, it plays a key role in achieving the sustainability targets of the transportation sector. To enable a modal shift from road to rail the German Aerospace Center has developed the Next Generation Train CARGO, a high-speed freight train concept targeted to ship so-called Low-Density High Value goods on existing railway infrastructure. Studies have revealed that an intermodal transshipment terminal is key to a successful integration of the concept in current logistics networks. Driven by high requirements regarding handling, reliability, and time, the terminal is a complex intralogistics system strongly depending on the particular good that shall be handled. This work uses the principles and methods of Model-Based Systems Engineering in a tailored modeling approach to specify a generic terminal system architecture. Based on this generic architecture an exemplary good-specific variant of the terminal is derived with focus on intralogistics freight handling. The chosen design approach is further evaluated regarding its suitability in context of intralogistics system design. The results of this work demonstrate that Model-Based Systems Engineering is capable of successfully guiding architecture specification in the novel application domain of complex intralogistics facilities and further contributes to a consistent and comprehensive terminal design.

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***Abstract*—Since rail traffic is the mode of mass transport with minimal transportation-related greenhouse gas emissions, it plays a key role in achieving the sustainability targets of the transportation sector. To enable a modal shift from road to rail the German Aerospace Center has developed the Next Generation Train CARGO, a high-speed freight train concept targeted to ship so-called Low-Density High Value goods on existing railway infrastructure from smart city to smart city. Studies have revealed that an intermodal transshipment terminal is key to a successful integration of the concept in current logistics networks. Driven by high requirements regarding handling, reliability, and time, the terminal is a complex intralogistics system strongly depending on the particular good group that shall be handled. This work uses the principles and methods of Model-Based Systems Engineering in a tailored modeling approach to specify a generic terminal system architecture. Based on this system architecture an exemplary good-specific variant of the terminal is derived with focus on intralogistics freight handling. The chosen design approach is further evaluated regarding its suitability in context of intralogistics system design. The results of this work demonstrate that Model-Based Systems Engineering is capable of successfully guiding architecture specification in the novel application domain of complex intralogistics facilities and further contributes to a consistent and comprehensive terminal design.**

Keywords—Model-Based Systems Engineering, intermodal terminal, high-speed rail freight transport, intralogistics

I. Introduction

The demand for mobility, both of goods and persons is expected to grow on a medium- and long-term time scale [1]. In order to meet the increasing demand for mobility and at the same time ensure a countervailing reduction in emissions, rail transport is regarded as a key player among the modes of transport because of the comparatively low greenhouse gas emissions [2]. Focusing on freight traffic the modal split strongly depends on the type of transported goods. Especially the so-called Low-Density High Value (LDHV) goods are almost exclusively transported by road or air cargo due to the high requirements regarding handling, time, flexibility, and reliability [3]. These are precisely the requirements addressed within the Next Generation Train (NGT) CARGO concept developed by the German Aerospace Center (DLR). The NGT CARGO is designed to facilitate high-speed rail transportation for these types of goods. By offering a competitive shipment of LDHV goods the NGT CARGO concept aims to contribute to the modal shift from road to rail for the main run of the corresponding logistics chain [4]. With an operating speed of up to 400 km/h the NGT CARGO allows for an optimized capacity utilization of the existing railway infrastructure by passenger and cargo trains and thus facilitates new rail cargo transportation concepts. A more detailed description of the high-speed freight train concept can be found in [5, 6].

However, a reliable and fast transshipment between rail and road or other modes of transport for the last mile is indispensable for a competitive intermodal transportation of LDHV goods [7]. This also applies to the successful integration of the NGT CARGO operations in the logistics chains of LDHV goods, as analyzed in [5]. According to [8], the LDHV good clusters intended to be transported by the NGT cargo are

- agricultural products, food, and beverage,
- textiles, paper, and printings,
- pharmaceuticals, machinery, and equipment,
- groupage freight,
- post, and parcels.

These clusters yield highly individual and good-specific requirements for handling and treatment within the logistics processes. Hence, the technology as well as the degree of automation for the transshipment is strongly related to the specific requirements. Further, it is stated that it is hardly possible to design an all-encompassing terminal, which meets all requirements of all types of goods at the same time [8].

Reference processes for the design of logistics facilities exist and are described in literature as established and mature [9, 10]. Yet, several aspects are criticized, such as problems of divisional thinking [11] and a premature focusing on obvious technical variants [12]. Great potential for improvement is seen in enhancing interdisciplinary communication and the use of digital models and tools [13].

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Therefore, the present work focuses on the development of a terminal system architecture facilitating intralogistics processes compliant with the diverse requirements and builds on the system analysis previously performed by DLR [8]. To demonstrate improvements in the logistics design process, this work proposes a requirement-driven and model-based approach, which is novel to this domain. Using means to manage high complexity, it is expected to contribute to a more consistent and comprehensive terminal design approach [14].

By applying the methodology of Model-Based Systems Engineering (MBSE), the terminal design can be decoupled from technological implementation. Therefore, use cases, activities, functional, and logical architectures are used to specify the generic tasks, behavior, and structure of the terminal supporting the transshipment of all types of goods. These specifications are documented and consistently traced to the individual requirements in a corresponding system model. Based on these generic specifications, an individual product architecture variant for the transshipment of a specific good cluster is derived by selecting and implementing appropriate intralogistics technologies for handling as well as storing. The resulting goals of this work are:

1. Model-based specification of a generic intermodal terminal architecture for the NGT CARGO following a customized modeling approach (chapters II and III)
2. Derivation of a product architecture as a good-specific variant of the generic terminal architecture (chapter IV)
3. Evaluation of the suitability of MBSE for a successful design of intralogistics systems embedded in a future smart city (chapter VI)

To reach these goals, chapter II presents a brief introduction to MBSE and the chosen modeling approach including the modeling steps. In chapter III the specification process of the generic system architecture is described. Based on the created common solution space, one exemplary product architecture variant of the terminal is derived in chapter IV. The findings on the architecture and MBSE as guiding methodology are discussed in chapter VI and a conclusion as well as an outlook is given in chapter VII.

II. Model-Based Systems Engineering (MBSE)

A. *Principles*

MBSE has its origins in the interdisciplinary and holistic system design approach of Systems Engineering (SE). Due to the rapidly increasing digitalization of all kinds of technical products and the increasing number of stakeholders, which are part of the system specification, design, verification, operation, and usage SE became a standardized practice and philosophy [15]. One of the essential outlines of SE is to guarantee a system design, which is compliant with the essential stakeholder needs, by emphasizing on the derivation and specification of system requirements. This leads to a front-loaded design process, which aims to reduce time and costly changes during late design phases [16]. It becomes clear that this approach is demanding a good communication with all stakeholders as well as clear, consistent, and transparent documentation of requirements and system specifications [17]. Based on this insight the practice of Model-Based SE has emerged. One of the goals of MBSE is to use a unique and consistent system model to document the diverse specifications during the entire design process instead of distributing the information in different types of documents. This system model represents an abstract proxy of the real system to engineer. It is the key artifact of MBSE and acts as a single source of truth. Based on the unique set of data, views are generated to display the information from desired perspectives. Key aspects implemented in the system model are the system's behavior, structure, requirements, and parameters [18]. The development of a system model in MBSE context is facilitated using a modeling tool, a modeling language, and a modeling methodology, also known as three pillars of MBSE. The tool is used to perform a set of tasks expressed in the selected language, while being instructed by the methodology. For each of the three pillars, different implementations exist. Since MBSE methodologies are no rigid procedures demanding for comprehensive adherence, customization regarding the individual needs and project objectives may be necessary to provide most appropriate guidance [19, 20].

B. *Tailored Modeling Approach*

In this work the Cameo Systems Modeler by No Magic [21] is selected as modeling tool together with SysML [22] as modeling language. As a guiding procedure, a tailored approach is specified based on two modeling methodologies, namely Systems Modeling Toolbox (SYSMOD) [23] and the Functional Architecture for Systems (FAS) method [24]. Due to the choice of methodology, the applied SysML language is extended by the SYSMOD Profile [23] especially affecting stereotyping. The approach is further enriched with additional domain-specific modeling activities to target logistics aspects, as well as verification and validation activities. The deployed activities within the modeling approach do not imply time-related sequence. Instead, iterative and parallel execution is required.

On a macro level, basic steps to derive and model the terminal architectures are:

- Specify a system process based on a base architecture and use cases (section III.A)
- Develop a functional architecture realizing the transformation of system behavior to system structure (section III.B)
- Model a logical architecture to formalize a generic structure for the terminal's logical operations (section III.C)
- Implement a generic toolbox for variants of intralogistics systems as solution space (section III.D)
- Derive a good-specific product architecture variant (section IV)

Various inputs from the previously conducted system analysis are implied, such as stakeholder analysis, the terminal's requirements, and top-level system process. As main outcomes, the customized modeling approach presented in this work delivers the generic terminal system architecture including the base, functional, and logical architectures. Together with the additionally modeled solution space the specification of a good-specific variant of the terminal is facilitated.

III. Design of Generic System Architecture

A. Base Architecture, Use Cases and System Process Specification

A fundamental principle of logistics systems is, that the processes determine the structure [9]. Thus, the starting point of architecture modeling is defining the basic logistics system process taking place in the terminal. However, the system process itself needs an initial framework, considering preset decisions regarding technologies, requirements, and system boundaries. This framework is given by the so-called base architecture [25].

1) Base Architecture

The terminal's base architecture is displayed in Fig. 1. Within this work the material handling system, denoted as terminal core and marked with a red frame in Fig. 1, is the chosen system of interest (SOI) that shall be further specified. To exclude building systems, structure, and energy supply from modeling scope, the terminal core is physically embedded in a logistics terminal building out of SOI's boundary. For information processing, the terminal core is connected to the warehouse management system (WMS) as key information interface. Multimodal vehicle operation is facilitated by adding corresponding road infrastructure as well as a rail shunting yard. The scope of the terminal's intralogistics processes is limited by treating order picking and customs activities as external services which are not provided by the terminal core itself.

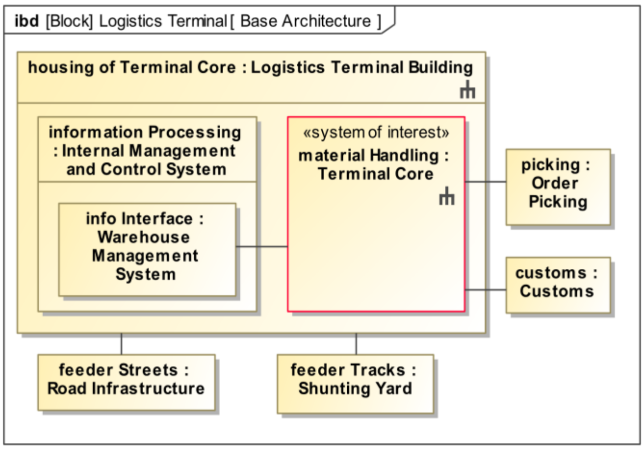

Fig. 1. Terminal base architecture with terminal core as system of interest.

2) Use Cases

By defining the system process based on use cases (UC), a user-centered development as well as compliance with functional requirements is supported. In this work, a UC is understood as a specific service of the system under investigation demanded by at least one actor [25]. Basic terminal services considered for the specification of the UC in this work are analogous to those of logistics distribution terminals as described by [26]. For the terminal core, six UC are derived:

- Receive, store and provide Freight
- Guarantee Freight Condition
- Evaluate Identity of Load Unit
- Communicate with Information System

3) System Process Specification

To derive the system process, the UC are modeled as interrelated actions in an activity diagram. The corresponding UC activities exhibit inputs, outputs, and connecting object and control flows. Hereby, the isolated terminal services are transformed into a logical sequence as terminal's top-level behavior. The main object flow facilitated by developed system process is the material flow in the terminal. As physically processed item, a load unit (LU) is defined, which refers to freight on either Euro-pallets or unit load devices (ULD) [5]. Processes to further decompose the LU are out of scope as the LU is regarded as unique flowing unit within this work. In contrast, as second type of object flow, information flow is treated only on a very basic level. Exchanged data is consolidated as so-called load unit information (LU Info) as flowing unit, including all transmitted information.

Each top-level UC activity calls a behavior of the terminal including several process steps. This behavior is implemented on a next level in the system model using further activity diagrams. The implied process steps are modeled as essential activities exchanging and processing LU and LU Info in various roles. As an example, Fig. 2 shows the activity called by the UC *'Receive Freight'*. This UC basically covers the service of collecting the freight from an inbound vehicle (LU at Road Vehicle/NGT Railcar) and preparing it for processing at other internal destinations respectively rejecting it in some circumstances. Thus, the UC activity contains essential activities for conveying, holding, checking, and internally conveying the inbound directed LU (top-down direction in Fig. 2). In parallel, LU Info is received, processed, and sent back to the WMS (left-right direction in Fig. 2). Implementation of control flows including signals enables the creation of a logical and process-driven sequence of essential activities.

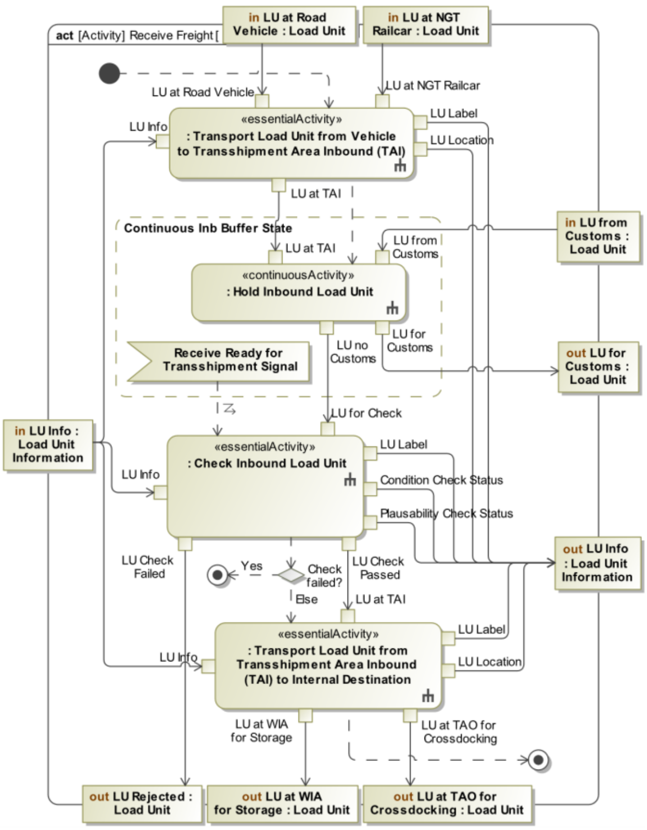

Fig. 2. Exemplary activity diagram for the UC activity *'Receive Freight'*.

To ensure a complete fulfillment of the requirements by the model, all activities are traced to the corresponding functional requirements. With progressing degree of process details, the modeled behavior increases in accuracy and domain-specific validity. However, the level of detail also directly affects the model's complexity, so that a bargaining among required accuracy and acceptable complexity is necessary. In this work, the terminal's behavior described by essential activities is assumed to be sufficient to proceed with the structural specification.

B. Functional Architecture

In a first step of structural specification, the essential activities of the system process defining the terminal's behavior have to be transformed into functions that describe the terminal's main tasks. The interactions of these functions yield the functional architecture [27]. To approach this step systematically, the FAS methodology is applied. Hereby, activities can be regrouped and allocated to abstract functional groups using activity trees provided by SysML. In this context, the functional groups cluster related activities with highest possible functional cohesion independent of the original UC. Superordinate functional groups, such as *Identification of LU* or *Movement of LU*, are determined based on the experience from the process specification and heuristics provided by the FAS methodology [24]. Applied heuristics are the grouping according to interface operations, shared data, or similar objects.

Subsequently, the defined functional groups are traced to functional elements to transit from a behavior-oriented to a structure-oriented modeling layer. These functional elements yield the functional structure [24]. Based on the corresponding essential activities, every functional element exhibits particular inputs, outputs, and interrelating flows. By implementing these functional interfaces with SysML ports, the functional architecture can be derived. Therefore, an internal block diagram (ibd) of the terminal core is created and the functional elements and interrelations are depicted. In addition, boundary functional interfaces are defined to model interacting functionality of the terminal core with its environment.

The functional architecture is the first comprehensive structural specification of the terminal core within this work. Yet, it has little in common with a typical physical system description, usually associated with structure. In contrast, the functional architecture is the most abstract representation of the system. The terminal is pragmatically reduced to a level, where no technical solutions are stipulated.

C. Logical Architecture

In this work, the logical architecture represents the structure for a logical processing of physical material flows. Thus, the use of message-driven SysML sequence diagrams as proposed by SYSMOD [23] is evaluated to be not appropriate to identify logical elements facilitating these material flows. Instead, the previously developed functional and base architectures are taken as initial basis for the derivation of the logical structure. Each of the different types of architecture is built to describe the entire system comprehensively. For the functional and the logical architecture, this implies that every function brought up by the functional elements has to be facilitated by the entirety of the logical counterparts. Thus, the objective of the following modeling task is to create logical elements that can be allocated to particular functions and comprehensively describe the terminal's logical operations.

In this context, a logical element is understood as a generic physical entity for the structural implementation of a particular logical operation. It has been found that an intermediate level of abstraction is facilitating the derivation and mapping of the logical elements. Therefore, the definition of logical subsystems is found beneficial to get an overview of initial physical units and to ensure a comprehensive description of the total system. In total, eight logical subsystems are initially defined for the terminal core:

- Road Vehicle Loading System
- NGT CARGO Loading System
- Check System
- Transshipment Area Inbound (TAI)
- Transshipment Area Outbound (TAO)
- Intralogistics Transportation System (ITS)
- Warehouse (WH)
- Condition System

As they are still too general to be directly allocated to functions in a reasonable way, the logical subsystems are subsequently decomposed to logical elements. Considering the intended behavior and tasks of logical subsystems, the logical elements are determined based on functional elements and act as conceptual realizations of the corresponding functions. It is important to state that functions and logical elements do not correlate in one-to-one relations rather than in n-to-m relations. The mapping of logical elements to the functional elements is displayed in Fig. 3. It shows the n-to-m relations among the most detailed level of functional and logical structure. These allocations represent the key transformation from functions into logical blocks. This transformation is crucial to ensure a comprehensive realization of the abstract functional entirety by the logical architecture. Apart from the aspect of completeness, the allocations enable a traceability from the terminal's behavior via its functional structure to its actual logical structure.

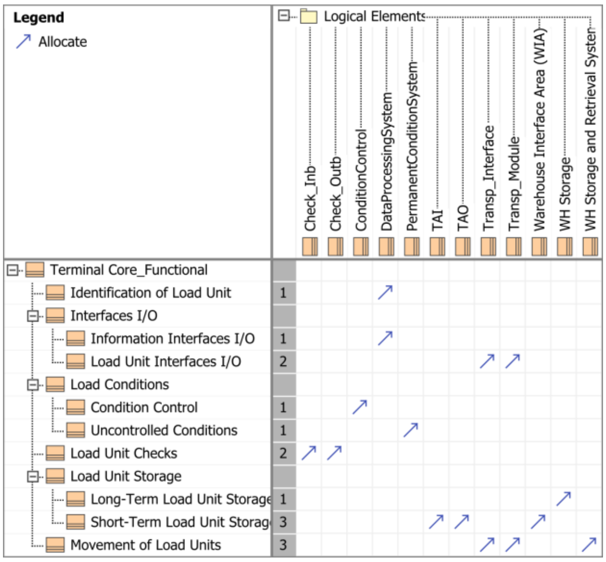

Fig. 3. Mapping of logical elements to functional elements.

The multidimensional relations between functions and logical structure reveal that different subsystems address similar functions. As a consequence, particular logical elements are allocated to more than one subsystem using different roles. For instance, the logical element *'Data Processing System'* (column four in Fig. 3) is part of every subsystem except the simple, non-smart buffer areas (TAI/TAO) and is designed to cover the functions for *'Information Interface'* and *'Identification of LU'*.

Analogously to the functional architecture, the logical elements and subsystems as well as the terminal core system block itself are equipped with SysML ports to realize logical interfaces. The defined logical structures are set into interrelating context by modeling material, information, and condition flows among these interfaces in accordance to the intralogistics process. The resulting artifact is the logical architecture, as depicted in Fig. 4. As basic structure, the diagram shows the eight previously introduced logical subsystems consisting out of the logical elements. Since this architecture represents a logical perspective, no spatial arrangement of subsystems is implied by the illustration. Each block exhibits a particular multiplicity. For instance, the terminal core is designed to contain at least one WH (which is the very right block in Fig. 4), although more than one WH are possible (denoted as [1..*]). The actual multiplicity depends on technical realization (technology, size) and is relevant for the design of good-specific and quantity-dependent product architecture variants.

In Fig. 4 the system's complexity already gets visible. However, the logical architecture is experienced as crucial to clarify actual flows, sequences, and their implications on physical terminal units. Additionally, it fulfills the task of being the intermediate step between the abstract functional description and a more concrete physical implementation of structure. As resulting artifact, it delivers a generic operational terminal layout, which is the baseline for subsequent development of a physical solution space.

D. Solution Space for the Product Architecture

The product architecture represents the lowest level of abstraction in the model and consists out of real technical system solutions [23]. The overall entity of implemented technical solutions forms the solution space. Apart from the generic logical baseline, this common pool of available solutions is the major baseline for variant creation, as it provides different technical realizations for the logical units.

Regardless of the selected good group and the amount of goods that shall be transshipped, the solution space is generic to every terminal variant. The terminal's solution space modeled in this work can be regarded as logistics systems toolbox. It covers seven basic classifications of physical logistics subsystems, such as storing systems, conveying systems, or freight check systems. They are implemented as physical blocks and allocated to logical elements, depending on their logistics role and functions. Each physical subsystem in the toolbox represents a corresponding set of equivalent, state-of-the-art technical variants. In case of the subsystem *storage systems*, variants, such as ground bulk storage, pallet racks, live storage racks or accumulation conveyors are implemented [11, 28]. To support the selection of the most appropriate variants based on the individual good-specific requirements, tailored evaluation criteria are defined based on [11]. The general suitability of implemented logistics systems is evaluated considering the targeted good groups (type and standardization of load carrier; temperature control). Key drivers for the selection of logistics evaluation criteria are capacity, rapid transshipment, and technical reliability as identified by [29], as well as a high, but realistic degree of automation [8]. With adding weightings to each criterion and rating the logistics systems based on [11], a basic evaluation support is created so that the toolbox can be applied systematically to yield a product architecture.

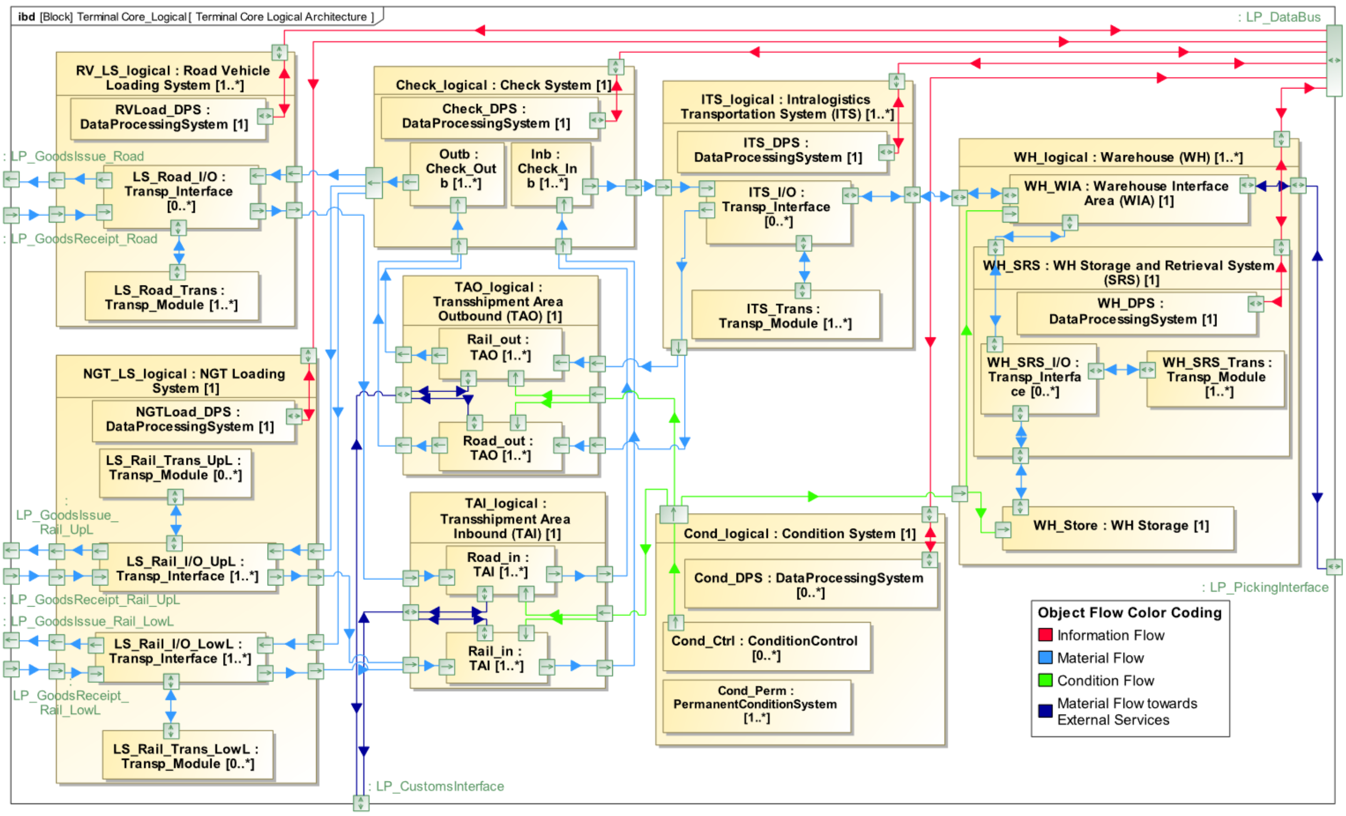

Fig. 4. Logical architecture of the terminal core, showing the logical subsystems, elements, and interrelations.

IV. PRODUCT ARCHITECTURE

Different decisions in design lead to different product structure variants with specific advantages and drawbacks, depending on the prioritized criteria when selecting the components. For sake of demonstration, one product architecture is derived for the good groups *'textiles'* and *'paper & printings'*, which are in general transshipped on standardized Euro-pallets and do not require special transshipment conditions, if hanging transshipment of clothes are disregarded. The step-by-step creation of the product architecture enforces plenty of design decisions. Specifically, decisions are made on parallelization and merging of material flows, distribution among different levels, or a bargaining between costs and efficiency. All these decisions demand a high domain knowledge regarding deployment and characteristics of logistics systems as well as the specific good's transshipment requirements. Additionally, the targeted throughput of LU is an important factor influencing the intralogistics terminal design. An NGT CARGO railcar is designed to carry up to 100 LU, so that the handling of a block train requires rapid transshipment of 1000 LU for each direction, inbound as well as outbound [30]. Depending on the frequency of arriving trains, this has a major effect on the choice of appropriate intralogistics solutions.

The resulting product architecture is still a conceptual development since no spatial arrangement, quantities, or size dimensions of the elements are considered at this point. The product architecture is implemented as a variant of the general terminal system block. Values and attributes are assigned to further specify the variant. This way of modeling enables an inheritance of all so far modeled tracings and allocations of requirements as well as functional, logical, and physical layers. This is displayed by Fig. 6 showing the overall tracing from structure via the behavior to the specification. In this case, an automated guided vehicle is selected to facilitate the loading activity towards road vehicles in the product architecture variant (the yellow block in the lower left corner). This automated guided vehicle is a type of discontinuous conveying system (green blocks, equals toolbox classification). The generic physical block is linked with allocation relationships to its logical (red blocks) and functional (blue blocks) structural counterparts. Further, Fig. 6 displays the tracing transition from structure to behavior via the functional groups (grey blocks) to the corresponding essential activity (orange block) and the UC. Finally, the behavior is directly traced to a specific requirement.

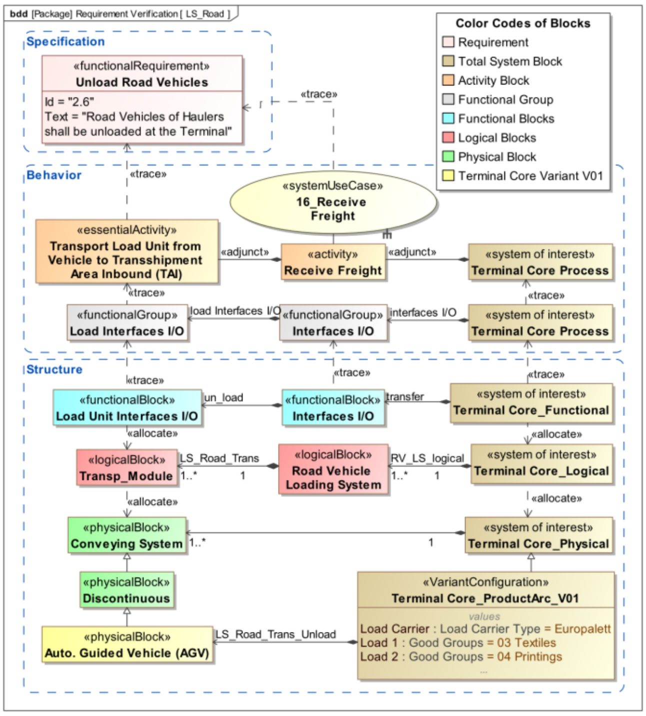

Fig. 6. Requirement tracing for elements of product architecture.

V. PHYSICAL ARCHITECTURE

Finally, a digital rendering of the terminal is created based on the derived product architecture, which represents a physical architecture for the chosen good group (Fig. 5). spatial relationships among the intralogistics systems are considered for the first time. The picture shows the train being loaded and unloaded by a continuous conveying system as well as the transshipment to other modes of transports and the warehouse storage. The physical architecture or rather the rendering enable logistics experts to examine the logistics plausibility of the designed terminal variant without necessarily being capable of reading SysML diagrams. Within this interview-based verification process 26 of 29 relevant requirements are evaluated to be either completely, or partially fulfilled. The latter are in particular performance requirements, which cannot be completely assessed by the examining the rendering or the product architecture. For a verification of these requirements simulations of the material flow need to be conducted terminal to evidence that the product architecture fulfills these requirements.

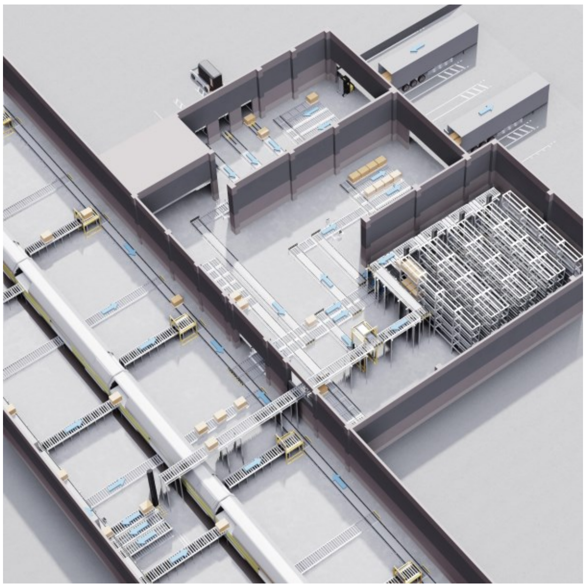

Fig. 5. Digital rendering of the terminal based on the developed variant.

VI. DISCUSSION

Independent from the selected types of good, the system's overall complexity is addressed by the modularization of the logical units and their physical counterparts. This is facilitated by consequent application of systems thinking and the top-down procedure inherent to the MBSE approach as proposed by [16]. In combination with the logistics toolbox providing various solutions with individual characteristics, the modularization is key to create a generic basis for all variants. Especially in regard to the heterogeneity of good-specific requirements, it becomes apparent that this is beneficial to cope complexity and is a major factor to success enabled by the application of MBSE. In addition, the modularization driven by the MBSE approach offers the potential to establish a portfolio of terminal variants with modular size extension (e.g. S, M, L, XL). Possible size parameters are number of tracks (parallel handling of multiple NGT CARGO trains) or length of tracks (single railcar, up to block train). Flexibility for extension is expected to be crucial to adopt the infrastructure to the individual future city or industrial location without creating operational inefficiencies or bottlenecks. In this context, it's important to state the issue of performance. An extension in terminal size does not only affect capacity of vehicle interface rather than the total intralogistics system with storage capacity and conveying system throughput [11]. To avoid bottleneck effects, the evaluation of performance is key. As touched on before, the validation reveals that no performance evaluation is possible with the model developed within this work. However, this is not caused by missing MBSE capabilities rather than by limited scope of this work. To cope this issue, a subsequent simulation of material flow is required to validate performance requirements and to make a statement about extension possibilities.

The means and tools provided by the chosen MBSE approach are experienced as sufficient to facilitate the derivation of the intralogistics process and corresponding terminal structure. The comprehensive advice for the processes (what to do) and the methods (how to do) facilitate a target-oriented, effective progress. This is a major advantage, which might address the missing connection between the static current logistics planning processes and the dynamic project progress itself, as criticized by [12]. The sequence of firstly specifying the system's behavior and then transiting it into the structure is found very helpful to keep the focus on functional requirements. The FAS method embedded in the customized SYSMOD approach has proven to be a useful facilitator of this transition. The resulting comprehensive understanding of the terminal's functionality is evaluated to be fundamental to a successful and effective development of the specific variant. Especially on the behavioral level, the holistic and iterative characteristics of MBSE can be a great chance to cope current problems in logistics design, such as divisional thinking, inherently inconclusive overall concepts [11], or the premature focusing on technical implementation [12]. Furthermore, the application of MBSE offers a completely new level of consistency and traceability across the whole specification process. By encouraging iterative modeling steps, the MBSE approach ensures that nothing is forgotten and thus enhances the level of completeness. Incompatible flows, violations of existing dependencies, or other logical errors are easily detected and prevented. The created system model acts as single source of truth. It enables a requirement tracing down to every single component of the variant. In this work, this is experienced as major impact on success.

However, the conducted MBSE approach reveals some disadvantages in context of logistics planning. The strongly formalized characteristics of SysML enforce a bargaining between semantic correctness and comfort in readability. Especially in regard to the product architecture, an experience made is that formally correct and complete MBSE views tend to be not suitable for communication with stakeholders. Here, additional visualizations are required. Alternatively, the derivation of a domain specific language as a SysML profile could be a possibility to enhance usability and comprehensibility of model views for logistics-specific purposes. Further, without continuously maintaining the model, inconsistencies occur. The maintenance of the model is found to be cumbersome, in particular for late changes, requiring various adjustments in the whole model.

Summarizing, the application of MBSE to the design of an intermodal terminal is a novel approach to improve logistics planning processes. Based on various experienced benefits, it is seen as great chance to support the specification of such complex infrastructure. Improvements especially in communication possibilities with stakeholders who are non-familiar with SysML modeling language are necessary. Embedded in the conducted research, MBSE has proven that it is capable of creating an appropriate solution for the NGT CARGO logistics terminal.

VII. Conclusion and Outlook

The intention of this research is to apply a MBSE approach to develop a detailed and realistic system architecture of the NGT CARGO logistics terminal. Further, the suitability of MBSE to support logistics design is evaluated. The selected MBSE approach is a combination of SysML, Cameo Systems Modeler, and a tailored SYSMOD approach, including the FAS method. The architecture design process comprises the investigation and specification of

- use cases and system processes,
- generic base, functional, and logical architectures,
- a logistics systems toolbox as solution space as well as
- a good-specific product architecture variant.

The subject-specific outcome of this research is a system model including a generic terminal system architecture with a corresponding solution space. These artifacts form the basis for the creation of terminal variants. One exemplary good-specific variant is derived, verified, validated, and visualized. Evaluation confirms that the developed terminal variant is both, plausible and reasonable from a logistics perspective. Regarding the architecture, the high level of complexity and the strong dependency on the good groups is managed by modular variant design and focus on homogeneous types of goods. The application of MBSE provides a systematic top-down approach supporting modularization. Together with enhanced traceability and consistency MBSE is attested a high potential to support current logistics planning. Yet, a conflict between required technical and methodical expertise is detected, which enforces effective collaboration among all stakeholders.

To enhance applicability of MBSE in the logistics domain, it is advisable to create a logistics stereotype profile or even a domain-specific meta model. Considering the logistics terminal, further investigation on the performance of the derived architecture is necessary, as the developed model is not capable of giving evidence that performance requirements are met. Suitable measures are additional expert interviews and of course simulations. The latter requires the derivation of models implemented in corresponding simulation tools and languages for different domains, such as AnyLogic, Matlab Simulink, or Modelica. Using the specified system model as single source of truth might facilitate the derivation of simulation models, their parameters and requirements that need to be verified. The interfaces between SysML and other modeling languages is thus assumed to be an enabler for the application of MBSE regardless of the engineering domain. Finally, the generic architecture should be used to derive additional variants, to target different good groups, and to develop a terminal portfolio. This is important to address the various logistics stakeholders of the heterogenic good groups and will further sharpen the concept of the NGT CARGO logistics terminal as part of a future-oriented flagship project for sustainable intermodal freight transport.

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