Exploring Evolvable Modular Patterns within Logistics

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Abstract—**Many domains employ the concept of modularity as a key aspect during their design. While the use of modularity characteristics is believed to enable several beneficial effects, such as evolvability, the actual realization of this evolvability or flexibility remains difficult. This paper analyzes a set of modular structures, which can be identified within transportation vehicles and logistic architectures. We employ Normalized Systems Theory (NST), a theory on how to create evolvable modular structures, as our theoretical basis to analyze these transportation and logistic structures in terms of the flexibility and adaptability they do (not) enable. For these structures, multiple design alternatives exist of which the theory can clearly highlight the respective benefits and drawbacks. This paper is an extended version of an earlier conference proceeding and demonstrates that NST is useful to analyze transport related modular structures at different levels of granularity. Additionally, we reflect upon the modularity characteristics of a recent logistics initiative called "The Physical Internet".**

Keywords–Modularity; Transportation; Logistics; Evolvability; Patterns; Physical Internet.

I. INTRODUCTION

This paper is an extended version of an earlier conference proceeding [1] in which the implications of applying Normalized Systems Theory (NST) to the modular architecture of transportation and logistics concepts is studied.

In many domains including computer science, product engineering, and organizational sciences, modularity has proven to be a powerful concept. A modular system is typically considered as a system, which is subdivided into a set of interacting subsystems. Several potential benefits are attributed to modular artifacts. Amongst other things, designing a product while using a set of modules is associated with a lower amount of complexity as the design is broken up into a set of smaller (less complex) problems [2]. Also, flexibility or evolvability are deemed to be improved in this way. Indeed, it allows one module of the system to be swapped for another version of it, without having to redesign the artifact from scratch. This allows some kind of plug-and-play behavior enabling variation (different aggregations based on the same set of modular building blocks can be formed) and evolvability (an artifact can evolve from one variant to another over time) and is deemed very powerful.

Achieving these benefits in reality is however quite challenging. Often, coupling (dependencies and interactions) between the modules in the system exist, which should be minimized [2][3][4]. However, specific ways on how this should precisely be done are often absent or ambiguous. For instance, some concerns in a modular system are cross-cutting (e.g., security in a software application) in the sense that their functionality is required throughout the entire system (e.g., every data entity should be securely stored). Adapting certain aspects of such cross-cutting concerns is often problematic as it typically creates profound ripple-effects throughout the system (i.e., a change in one module triggers a change in several other modules), which is clearly contradictory with the purpose of evolvability.

This paper focuses on the modular structures within the context of transportation vehicles and logistic architectures. It is clear that transportation vehicles (such as cars, trucks, boats, airplanes, trains) are modular structures at several abstraction levels (a car consisting out of a trunk, chassis, engine, etc. of which the engine consists out of several cylinders etc.) and could benefit from evolvability (e.g., replacing or upgrading particular parts or even extending the vehicle with additional seating places or engines). Also, the concept of cross-cutting concerns seems relevant within this context. That is, transportation artifacts need multiple auxiliary facilities in their design such as electricity and communication, which are needed in most of their components. More specifically, several of these auxiliary facilities within the modular design of physical artifacts (such as the different design options to distribute heating) were already discussed using an NST perspective in another publication [5] in a housing context. Analogous conclusions for these facilities can be drawn in the context of transportation artifacts. What differentiates transportation artifacts from other types of artifacts, is the presence of the additional and crucial concern of *propulsion*. Every transportation mechanism should, somehow, provide the ability for its cargo to be transported from one location to another. This propulsion can be realized by means of different driving mechanisms and different integration architectures, which will be the main focus of our exploratory analysis in this paper. However, most transportation vehicles are designed in such way that they lack true evolvability in several ways (e.g., extending the seating capacity of a car or adding additional cylinders in the engine is typically impossible). This paper studies the implications of different design alternatives for transportation vehicles and logistic architectures in terms of their evolvability. The considered design alternatives are based on the modular integration patterns as suggested by Normalized Systems Theory (NST) [6]. The theory is relevant in this context as it studies in-depth the necessary conditions in order to design evolvable modular systems.

It is important to mention upfront that none of the authors of this paper are experts within the domain of transportation or logistics. Therefore, the intention of this paper is not the prescribe in detail how architectures within this industry should be improved in the future. Rather, we intend to show that it makes sense to apply the modularity reasoning presented within NST (which originated at the software level) to this other domain in which we believe modularity is playing an important role.

The remainder of this paper is structured as follows. In Section II, we provide a brief overview of NST and the ways it describes to integrate the different modules within a system. We then apply these patterns to the analysis of transportation vehicles (e.g., cars, airplanes) in Section III. In Section IV, we analyze the modular architectures and integration of so-called cross-cutting concerns and ponder on some new initiatives and trends present within the logistics industry, which seem to exhibit certain similarities with NST's (more general) modularity approach. Finally, we offer our conclusions in Section V.

II. Modularity and NST Integration Patterns

A. *NST and combinatorics*

NST is a theory providing the formulation of design theorems, which are proven to be necessary conditions for obtaining an evolvable software system [6]. The authors operationalize evolvability by demanding Bounded Input Bound Output (BIBO) stability, even for systems growing in an unlimited way. The theorems prescribe that all change drivers should be separated in distinct constructs (Separation of Concerns), processing functions should be called statefully (Separation of States) and data structures or processing functions should be up-datable without impacting other data structures or processing functions (Version Transparency) [7]. Further, these theorems can actually be reformulated for modular systems in general [8] and related to basic combinatorics [6]. More specifically, it is illustrated that modularity suggests that maintaining a particular amount of versions of modular building blocks should allow for an exponential amount of available system variants. However, when modularity is applied arbitrarily (e.g., by not adhering to the theorems), changing one particular version of one particular module may result into ripple effects to other (versions of) modules. This number of impacts can exponentially grow with the size of the system, which is clearly harmful for the evolvability of a (software) system.

B. *Patterns for cross-cutting concern integration*

Adherence to the NST theorems results in a very fine-grained modular system. This fine-grained design should be established very meticulously as every violation of every design theorem is proven to result eventually into ripple effects due to change. This is very hard to achieve in practice and therefore, "elements" (i.e., modular design patterns) are proposed to enable the construction of such systems in a realistic setting [6]. Each of these elements provides a generic reusable modular structure for a basic functionality of the type of system one is creating. To fit the specific situation at hand, they can be parametrized and, if necessary, customized. A system is then created as being a set of parametrized instantiations of these generic modular elements. For software systems, data, task, flow, connector and trigger elements were defined as generic modular structures providing the basic functionalities of most information systems [6]. One can therefore conclude that the modules forming an element become (as a whole) a reusable module at a higher level of abstraction. Internally, every element takes care of a core functionality (e.g., the representation of data), and provides integration with some relevant cross-cutting concerns for that system (e.g., data security and persistency). To maximally enable evolvability, these cross-cutting concerns need to be integrated at the lowest modular granularity level possible (forming elements). The parts in the elements connecting or dealing with the cross-cutting concerns need to be properly isolated in separate modules being version transparent.

In general, different integration patterns for dealing with cross-cutting concerns can be distinguished. One possibility is to add cross-cutting concern modules directly to the main modules. Each cross-cutting concern module will then, by itself, handle the full functionality of that cross-cutting concern. We call integrations of this type the *embedded integration pattern* and will refer to it as *configuration 1*. More specifically, such embedded module can either be dedicated (i.e., the module was specifically designed for the considered system) or standardized (i.e., a standardized module for handling the cross-cutting concern is chosen). The first option is referred to as *configuration 1A*, while the latter one will be referenced as *configuration 1B*. In the context of software systems, imagine for instance a separate module added to a data entity to take care of data persistency in a custom designed way (1A) or by adopting a standard module (1B) for the same goal.

Another possibility is to add the cross-cutting concern modules to the main modules in such way that the cross-cutting concern modules only act as connections (or "relay modules") to an (external) framework, which implements the cross-cutting concern more elaborately and will therefore actually perform the needed functionality. We call integrations of this type the *relay integration pattern* and will refer to it as *configuration 2*. More specifically, a relay module can link to a dedicated framework (i.e., the framework was specifically designed for the considered system) or standardized (possibly even publicly available). The first option is referred to as *configuration 2A* while the latter one will be referenced as *configuration 2B*. In the context of a software system, imagine for instance a separate module added to a data entity acting as a proxy to a specifically designed persistency framework (2A) or to a widely used standard solution, such as Java Persistence API (2B). Finally, it is also possible to have a relay module connecting to a *framework gateway* module. Here, it is only the framework gateway that connects directly to the external framework. This third variant is referred to as *configuration 2C*. In the context of a software system, imagine for instance a dedicated gateway module that connects to the JPA framework allowing all cross-cutting concern relay modules to call the gateway without being dependent on JPA themselves.

As a modular field matures, it will create several levels of granularity among which it will need to integrate its relevant cross-cutting concerns. Also, the concern will typically be embedded at a deeper level (i.e., more fine-grained), and towards a more standardized (from A to B) and relayed (i.e., 2B and 2C) way.

III. TRANSPORTATION VEHICLE PATTERNS

The identification of modules within a system is often a recursive issue [2]: at different levels of granularity, parts and subparts can be discerned. Therefore, when studying modularity within the domain of transportation, we propose to focus on the modular structure and its integration patterns at different levels: the vehicle, cargo and vehicle component levels.

A. The vehicle level

Regarding transportation, it is clear that most types of vehicles (such as cars, trucks, airplanes) provide their own propulsion mechanism, both in terms of power storage (e.g., fuel) and energy generation (typically by means of an engine). Since in most cases, extensively tested and highly standardized modules are used for this purpose, this clearly aligns with integration pattern 1B as introduced in Section II. This has benefits in terms of flexibility: different types of vehicles might use different types of power source (e.g., diesel, gas, electricity) or have different power needs (e.g., related to the cargo capacity). It also provides a high amount of independence and autonomy. A downside of such an architecture is clearly that the propulsion mechanism needs to be, by definition, embedded within every individual transport vehicle and that for instance technological advancements are not automatically dispersed over all available vehicles unless each of their mechanisms (e.g., engines) are individually updated or replaced. Another drawback is the fact that this does not allow the realization of any possible economies of scale arising from producing energy on a larger scale (i.e., for many vehicles at once).

While the other integration architectures are used less frequently, they are not completely inconceivable for transportation vehicles. Consider for instance an electrical train. While the propulsion forces are generated internally using electrical engines, the electrical power used for this purpose is generated externally. This electrical power is tapped from an externally available framework or, in this case, the electrical distribution network available along the train tracks. Therefore, one could argue that —to a certain extent— this aligns already to some extent with integration pattern 2B. One could even go one step further. Consider for instance the case of the Transrapid magnetic levitation train, or the recently proposed Hyperloop. In these types of transportation, the vehicles are propelled by the propulsion forces generated in or around the vehicle tracks. This would even more narrowly fit into the mentioned integration pattern 2B. While such centralized architectures introduce a dependency on the external framework employed (e.g., if the energy distribution network is down, no vehicle will be able to advance), they have clear benefits as well. For instance, they would be able to benefit from economies of scale regarding efficiency, or flexibility with respect to the introduction of (for instance) more environmentally friendly techniques for power generation.

Returning to the design of cars, it is clear that such mechanisms (i.e., as described in integration pattern 2) would only be possible in case the roads contain propulsion mechanisms or conduct power. As this is currently not the case, the electrical power for electrical cars can only be stored internally in batteries (but generated externally) and the design of the distribution mechanism for propulsion remains tied to integration pattern 1B. Specifically focusing our attention on airplane vehicles, one can note that aircrafts require large amounts of propulsion power, which would make the use of an architecture in which the aircraft taps into an externally available standardized framework via a relay module (i.e., integration pattern 2B) extremely tempting. Nevertheless, the intertwining of propulsion and lift (which is specific for aircrafts) would make this design very difficult, and the notion seems to be completely incompatible with the current degrees of freedom airplanes enjoy to use the airspace. Indeed, such an architecture would entail the need for some kind of tubes encompassing the vehicles, which could in their turn remove the need for lifting forces. In other words, such an architecture would probably cease to be genuine air transport.

Nevertheless, as this configuration has been realized for certain transportation vehicles and offers potential for others (e.g., cars) in the future, we believe that the exploration of (the feasibility) of technologies enabling these kind of integration architectures would be very worthwhile.

B. The cargo level

It is interesting to note that the transportation industry has already, rather explicitly, adopted a high degree of modularity standardization at the level of their cargo. This can be found in the context of today's logistics landscape, in which it is important to be able to transport goods by means of cross-mode transportation. That means that, in order to go from point A to B, multiple vehicles of often different nature are employed. For instance, a laptop ordered in the USA to be delivered in Antwerp, might travel by a combination of airplane and/or boat, train, truck and car. In order to facilitate such logistic routes, the packaging of the cargoes (i.e., the goods to be transported) are packaged, is standardized to a large extent by means of *containerized freight*. That is, while for some type of goods customized transportation mechanisms still exist (e.g., for the transportation of steel coils, roll-on roll-off (RoRo) goods, bulk goods, etc.), the majority of non-bulk goods is transported by means of containers. Such containers can clearly be considered as standardized cargo modules in terms of several of their properties such as their dimensions (height, length, depth), securing mechanisms, maximum load, etc.

From a modularity point of view, one can see that in such case various sound design principles are applied, implying a set of accompanying important benefits. First, this existing containerized modular freight architecture enables the decoupling or encapsulation of the cargo from the transport vehicle (cf. infra). This decoupling allows to freely combine both decoupled parts (here: cargo and transport vehicle) without having to adapt one or the other for this purpose. Stated otherwise: substitution of the modular parts is made easy. Indeed, the standardization of freight containers in terms of dimensions and securing mechanisms allows the recombination of goods on different transportation modes at the level of the individual containers. As long as goods can be securely stowed within these standardized containers, thousands of them can be loaded by cranes on sea-going cargo ships, be switched to barges in batches of tens or maybe hundred containers, routed individually within a harbor, and further shipped towards customers via trains (in a set up to 20) and/or trucks (mostly individually). Similarly, as most transportation vehicles are designed in correspondence with the standardized dimensions of the freight containers, they can transport all types of goods and do not need to undergo specific changes when, for instance, a truck has to transport couches instead of laptops. Second, the modular architecture of the cargo makes it possible to upscale or downscale the total cargo on one vehicle within certain limits. For instance, as long as a ship is large enough, one can extend the overall cargo by simply increasing the number of containers. Or, as long the traction of a locomotive is powerful enough, additional containers can be added to a transportation train. We therefore conclude that already an important amount of flexibility is achieved in terms of the type of cargo as well as the transportation mode and scale.

Interpreting the situation sketched above in terms of our modular integration architectures as described in Section II, this means that integration architecture 2C is applied. That is, it is clear that no embedded architecture is present as the container itself has no propulsion mechanisms incorporated into it. Instead, the container has standardized connections to connect into different types of vehicles (see Section III-A) which, at their turn, have the capacity to provide the required propulsion for one or several containers. As these connections are version transparent in terms of a large set of different vehicles (truck, train and even boat), no dependency regarding a specific type of external network is present and therefore we would be inclined to categorize the propulsion provisioning in this situation as using architecture 2C.

Further, in terms of this containerized freight, it is important to mention that, conceptually speaking, the idea of containerization should not necessarily be limited to freight alone. For instance, one can easily imagine that similar cargo modules could be made for humans as well, although such containers would clearly have to be made more human-friendly, and the practicality and added value might —at this point in time— be questionable.

Finally, it is interesting to note that certain players in industry are still looking for additional ways to modularize freight in a more efficient way. For instance, Airbus was only recently —in late 2015— granted a patent for a modular removable aircraft cabin, in which the whole cabin (i.e., the space for all passengers) can be substituted by another cabin [9]. The fact that major industry players are working on these kinds of ideas, seems to support the fact that such ideas on modularization in (air) transportation should definitely not be considered ludicrous nor obvious.

C. The vehicle components level

In order to further explore the modular integration in the context of transportation vehicles, it is interesting to ponder on the decoupling or encapsulation of the various concerns at the level of the vehicle components, such as those of a car. Here, relevant concerns could be the passenger cabine (providing a comfortable place for passengers to sit), the trunk (providing storage space for luggage), the chassis (protecting the car from the outside world) or the engine (generating the propulsion force). It is remarkable to note that, in many cases, the compatibility of these modular components of transportation vehicles seems restricted to vehicles of one particular model or, in some cases, multiple models of one manufacturer. This means that, when again considering a car, most passenger cabines, trunks, chassis parts, etc. can only be replaced by their exact copies. Stated otherwise, a trunk that was designed for car model A is typically not able to be used for a car model B as it would simply not fit due to size limitations, aerodynamic constraints, weight, etc. This is due to a high degree of coupling between the individual components we consider and their model or manufacturer specifications. It would certainly provide some added value to customers if the modules implementing these major concerns would be decoupled, encapsulated, and standardized in accordance with integration architecture 1B as discussed in Section II, allowing plug-and-play behavior. In such case, consumers would for instance be able —for a certain car size category— to purchase the chassis, the engine, the passenger cabine, the trunk, etc. all independently from different vendors.

Moreover, each of these modules could then be replaced or upgraded independently as well. For example, the engine could be replaced when it breaks down, but could also be upgraded in order to have a more powerful, modern, or environmentally cleaner engine. One could even imagine to introduce an electrical engine in a car that was originally equipped with as gas or diesel engine. Of course, we mention once again that we are no experts in car manufacturing and do not elaborate on the specific manufacturing details of each aspect of the design. Moreover, we are aware of the fact that it would not be straightforward to keep the decoupling or encapsulation of the various modules intact throughout the course of significant technological evolutions in time. Nevertheless, the advantages of such design from a sustainability point of view would obviously be significant: cars could become more efficient and cleaner without ending up in a junkyard after a limited amount of years.

Some indications suggest that the amount of coupling between vehicle components or between the vehicle and its components is not equally large among different industries. For instance, the airplane industry seems to succeed in having a better decoupling and encapsulation of certain parts of an airplane. For example, manufacturers of jet engines and the aircraft are typically different firms. In order to remain viable as an industry, this implies (and necessitates) that the engine and the rest of the vehicle should, at least to some extent, be decoupled. However, though an engine can be replaced, aircrafts are clearly designed for a certain type and amount of engines.

Considering the components of transportation vehicles at a still more fine-grained modular level, one could imagine an even more fine-grained modular structure for, for instance, car engines where cylinders could be replaced, upgraded, or simply added in order to increase the engine power. Again, in order to enable these possibilities, the modules at this very fine-grained level should be designed in such a way that they are clearly decoupled, encapsulated and standardized, corresponding to integration architecture 1B.

D. Overview and advanced issues

Table I provides an overview of the granularity-integration pattern combinations for the case of transportation vehicles. We can observe that an interesting and advanced modular architecture already seems to be in place at the cargo level. This tends to indicate that the industry has reached a rather high maturity level regarding this issue. As far as the vehicle and vehicle component modularity levels are concerned, interesting avenues for a further exploration of the modular integration architecture can be remarked. This certainly holds for the case of vehicle components, where the design of fully decoupled and encapsulated modular parts still seems to be in-progress. The table further illustrates that, when aiming for maximum flexibility, the integration of concerns tends to be solved at more fine-grained levels (going downwards in Table I) and in a more standardized way enabled by an external framework (going to the right in Table I) in the long run.

Furthermore, it is interesting to make the mental exercise of applying NST reasoning in a more complete way and adopt the notion of NST elements, which we introduced in Section II. When employing such elements to build a system, a large set of very tightly integrated, small and fine-grained modules are used to form the aggregated system (instead of one monolithic and non-scalable building block). Translating this idea to the components of an engine, one could imagine an engine as an aggregation of smaller integrated engines (with all required subcomponents for a small engine) delivering propulsion forces. This would theoretically mean that the propulsion power could be increased by adding more engines, and that the various small engines could be replaced and upgraded independently, even combining combustion engines and electrical engines. Once again, this could have significant benefits from a sustainability point of view. Also, this would partly solve some of the scalability issues we mentioned in Section III-A, for instance in cases when carrying additional cargo within a particular vehicle would be restrained due to limitations in the capacity of the vehicle's engine.

TABLE I. OVERVIEW OF THE DIFFERENT GRANULARITY-INTEGRATION PATTERN COMBINATIONS REGARDING TRANSPORTATION VEHICLES

	1A	*1B*	*2A*	*2B*	*2C*
vehicle		●		○	
cargo					●
vehicle components		○			

●: currently employed, ○: to be explored

Going one step further, elements might be conceivable at a higher granularity level as well. That is, elements might be designed that also provide the integration of these small engines with non-propulsion concerns. Suppose for instance one-person transport modules or vehicles that can be aggregated or combined at any time into more-person modules. Assume further that these one-person modules have their own propulsion mechanisms and storage spaces, which are automatically combined when several modules are aggregated. This would mean that the propulsion power and the storage room would be proportional to the size of the vehicle, which would be proportional to the number of passengers. And one could further imagine that each one of those units could be enabled to tap into external propulsion power if available (cf. integration architecture 2B or 2C), while producing its own propulsion power otherwise (cf. integration architecture 1B).

One could even explore what this could possibly mean for air transportation. When considering the design of airplane artifacts, one can note that they differentiate themselves from ground transportation artifacts by the fact that another concern next to propulsion becomes apparent: the need to obtain lift. Adding this concern to the design is obviously not trivial. Indeed, both concerns —propulsion and lift— are even tightly coupled in current airplanes: the lift force is based on the velocity and therefore on the propulsion of the vehicle. This actually represents an omnipresent risk in airplanes: without propulsion, there is no lift anymore. Nevertheless, we do think that a similar reasoning based on elements is valid for air transportation. For instance, one could imagine small integrated transport modules or vehicles for a few persons, that can be aggregated or combined at any time into larger airplane modules. From an energy or sustainability point of view, it would clearly be very appealing to be able to adapt the size and propulsion power of the airplanes to the number of registered passengers.

As we are no domain experts, we are clearly not entitled to discuss the outlook of modular structures for transport propulsion in depth or judge on their practical feasibility. We also do not have any intention to oversimplify the difficulties and complexities one would be confronted with during the design of such elements. For example, the design of such modular architectures obviously does not liberate the designer from the laws of physics that need to be obeyed at all times: when considering the elements for air transportation, the relationship between the weight of the vehicle and the wing surface creating the lift, should result in the required equilibrium at the cruising speed, both for the singular and aggregated vehicles. However, instead of making such architectures impossible, these physical constraints could serve as boundary conditions to solve the design equations. So, instead of elaborating in detail on the actual design of such modular building blocks (such as the elements), our main goal is to illustrate the relevance of our modularity approach for the design of transportation vehicles and to show what kind of possibilities normalized evolvable transport architectures could unleash. For instance, the scalability issue mentioned in Section III-A, would probably be largely solved if the industry would manage to realize such elements.

IV. LOGISTIC ARCHITECTURES

Whereas Section III focused on the modular architecture of (individual) vehicles, the viewpoint of modularization and its integration architectures can also be applied at a higher conceptual level such as logistics in general and its associated supply chain. That is, transportation can and is increasingly considered as a type of service, i.e., the service of something being transported from place X to Y in a timely and not too costly fashion. How the transportation is precisely executed (with which transportation means, at once or in several stages, etc.) is often of less or sometimes even no importance. Considering transportation as a service often also shifts the responsibility of collecting the remuneration or payment from the client to the scope of the service provider. For instance, one might think of situations where a client is prepared to pay a certain fee for the transportation of a particular good from location A to B by point in time P, and in which it is the service provider's responsibility to determine how this will be performed.

It is particularly interesting to see how recent initiatives in the business world are being taken in the context of this servitization. In this section, we will focus on two aspects of this servitization and their relation to the modularity aspects we discussed above. First, in Section IV-A, we focus on the (public) transport of people and the emergence of Mobility-as-a-Service (MaaS). Next, in Section IV-B, we focus on how the Physical Internet (PI) is aiming to revolutionize the transportation of goods.

A. *Mobility-as-a-Service*

The emergence of the concept of Mobility-as-a-Service is primarily driven by the idea that, given the increasing number of people living in major cities, it becomes unsustainable to have each individual person possessing his or her own car and use that for their private transportation needs. Some of the problems associated with such situation include the exploding amount of traffic leading to congested roads and associated traffic jams, increased pollution and the fact that it is inefficient in terms of capital spending (i.e., the high expenses of having a dedicated car including its insurance, maintenance, etc. for a device that is often more than 90% of the time unused). Therefore, the mission of MaaS and most of its providers is to enable consumers to make the switch from primarily using private cars for their transportation means towards (sustainable) shared mobility resources (such as taxi, car sharing, tram, bus, train, bike) or, stated otherwise, "to make it easier and more rewarding to use sustainable modes of transport in urban areas" [10, p. 4]. Attempts towards this direction could be, but should not necessarily be limited to [11]:

- *Simplified car ownership*: car manufacturers offering services that enable the usage of one physical vehicle with multiple owners. On top of financial services to handle purchasing and leasing, technological services (e.g., scheduling of vehicle use) and cost distribution calculation services are offered. The primary motivation behind these initiatives is presented as a reduction of the inefficiency of capital spending.
- *Peer transport services*: while initiatives in the simplified car ownership category focus on reducing the inefficiency of capital spending but remain within well-trusted boundaries of an individual's network, peer transport services seek to radically remove these inefficiencies by leveraging the excess capacity of all nearby means of transport. Available transport capacity is offered through a digital platform, where algorithms determine optimal matches between demand and supply. In this category, the service providers do not own the physical means of transport themsevles. Rather, they provide the technological platform and offer payment services.
- *Car sharing*: in car sharing initiatives, an organization commits itself to ownership of a fleet of transportation means. As a result, a more consistent and reliable service can be offered when compared to the previous categories.
- *Extended multi-modal planner*: a company offering advanced planning services by suggesting customers routes that may involve a combination of different transportation modals if those options appear to be the most efficient onces. Obviously, such planners might allow you to buy a ticket for the suggested route as well.
- *Combined mobility services*: a neutral third-party company that combines multiple mobility services as one offering (one subscription, unified invoicing, etc.) towards its customers (often complemented with an app for mobile devices, a website, etc.).
- *Integrated public transport*: focusing on the combined offering of public transport options, but optionally combined with other modes of transport as well.
- *Mobility broker*: similar mobility subscriptions as the options described above, but offered as part of a house rent. The mobility services are therefore required to be incorporated within the general planning process of urban areas.

As multiple sustainable transportation means are available for customers, customers could (in theory) choose from different alternatives (on a day-to-day basis) for the same transport or even combine several of them within one voyage. This often requires customers to manage a complex set of tickets or subscriptions that may turn the whole trajectory into something quite expensive and restricts the traveler's comfort. Therefore, the rationale behind MaaS additionally aims to enable customers to actually make use of this myriad of transportation means in the combination and timing they prefer or need (e.g., on day 1 using a combination of tram and a shared bike to go to work and on day 2 a shared car due to the rainy weather) in a comfortable way, i.e., by subscribing to only one provider or platform. Indeed, as Kamargianni et al. mention, "the complexity of using a variety of transport models (i.e. different payment methods, subscriptions, different mobile applications for each operator, lack of integrated information etc.) discourages many people from taking advantage of them" [12, p. 3295].

Therefore, an important characteristic of MaaS is its ability to provide *integration* for the customer in order to improve user friendliness and adoption. Some conceptualizations of MaaS would therefore only consider bullet points 4 till 8 as genuine implementations of MaaS as only these variatns include the combination (and therefore require the integration) of different types of transport. Conceptually, the goal is clearly to provide an integration of all the shared mobility resources for the customer. This issue has been formulated in a more specific way by Kamergianni et al. by splitting up the general concept of integration into three main elements [12, p. 3295]:

- *Ticket & Payment integration*: having one ("smart") card to be able to pay within different modes of transportation;
- *Mobility package*: a package for customers in which they (pre)pay for different modes of transportation;
- *ICT integration*: providing a digital integrated interface (often for smartphone) to give a single point of access regarding information for each of the different modes of transportation.

While the ICT integration between the different mobility providers is obviously challenging and crucial for a fluent user experience, we do not further focus on this issue in the remainder of this section. Rather, we will pay attention to the first two main elements listed as they both are related to payment issues and provide an interesting angle to look at a non-tangible part of each transportation service: the remuneration a mobility service provider should get for offering its services. Additionally, the integration of ticketing and payment are considered as stages necessarily preceding the ICT integration phase [13]. As all transportation services have to be remunerated in one way or the other, one could argue that this constitutes a genuine cross-cutting concern for mobility services: whether you take the tram, bus, taxi, shared car, etc., there will always be one or multiple mobility provider(s) that has/have to be compensated for the efforts performed. Therefore, our modularity approach and the adjoining reasoning regarding cross-cutting concern integration patterns is considered as a useful point of view in this regard. Specifically in a context where multiple mobility services are present and can be used during one voyage, interesting questions on how to integrate this concern in an efficient way, arise. First, we discuss how the payment concern is currently integrated in logistics (i.e., pre-MaaS). Next, we analyze how MaaS attempts to change this and reflect on the question whether we can still see some possible points for improvements based on our theoretical basis. For this end, similarly as we did in Section III, we will make use of tables representing different modular aggregation levels and how the cross-cutting concern is or can be integrated at each of these levels. It is important to be aware that in Tables II and III, we clearly consider another cross-cutting concern than in Table I. Whereas the latter focused on the integration of the propulsion concern for transportation vehicles, the former tables will focus on the integration of the payment concern for mobility services.

TABLE II. OVERVIEW OF THE DIFFERENT GRANULARITY-INTEGRATION PATTERN COMBINATIONS REGARDING THE REMUNERATION OF MOBILITY SERVICES IN A PRE-MAAS CONFIGURATION

	1A	*1B*	*2A*	*2B*	*2C*
mobility provider		●			
trip		●		●	

●: currently employed

In order to analyze the pre-MaaS phase, we consider Table II. Here, only two rows are included, i.e., trip and mobility provider. Typically, it is possible to pay directly for a single trip in cash when using a public service provider (e.g., at the cab or bus driver), which would correspond to the integration of the payment cross-cutting concern by means of configuration 1B (1 because it is embedded, B because generally standardized cashier systems are being used). However, many of these public transport providers also offer subscriptions or multi-ride tickets. A devaluation mechanism is then typically present in the vehicles, registering for instance an additional ride on the multi-ride ticket or verifying the validity of the subscription card. As a consequence, this corresponds to integration configuration 2B at the level of the trip (i.e., the payment is being performed but in a relay fashion as a connection is made to an external framework at a higher modularity aggregation level, here: mobility provider) and integration configuration 1B at the level of the mobility provider (e.g., bus or tram company) as the actual payment is made here in a dedicated way. Remark that at the level of the trip, integration architecture 2B still implies that the connection to the mobility provider is specific for the particular provider the customer is using (e.g., the bus company one is making use of). This also implies that a customer will be required to engage in multiple subscriptions or multi-ride tickets for each mobility provider of each transport mode one is making use of.

TABLE III. OVERVIEW OF THE DIFFERENT GRANULARITY-INTEGRATION PATTERN COMBINATIONS REGARDING THE REMUNERATION OF MOBILITY SERVICES IN A POST-MAAS CONFIGURATION

	1A	*1B*	*2A*	*2B*	*2C*
mobility platform		●			
mobility provider		●		●	○
trip		●		●	●

●: currently employed, ○: to be explored

As mentioned above, precisely this issue (which can be derived from Table II) was one of the driving forces behind the idea of MaaS: avoiding the need for consumers to buy separate (multi-ride) tickets or subscriptions for each of the mobility services one is using as this inefficiency is assumed to be an important obstacle for people to start using a (combination of) the available durable public transport means in a city. The offered alternative can be represented by means of Table III. Remark that an additional row is added to the table, i.e., the mobility provider platform. This level becomes relevant in situations such as MaaS where an aggregation of multiple service providers is envisioned. When further analyzing the table, one can find that 1B (standardized dedicated) payments at the level of a trip are typically still possible (as was the case in the pre-MaaS situation), which is therefore not a differentiating characteristic for MaaS service models. Also the traditional one-provider subscription mechanism remains available (a 1B configuration at the level of the mobility provider and 2B configuration at the level of the individual trip) but is equally not a differentiating characteristic for MaaS service models. However, as soon as one considers MaaS as a new concept, the payment can also be performed at a higher and additional modular aggregation level (i.e., a mobility platform) providing a customer the possibility to, for instance, sign up for one subscription and have access to several transportation means (e.g., tram, bus, bike and car sharing). Therefore, at the level of this mobility platform, this corresponds to integration architecture 1B. Regarding the trip level, the integration architecture can move from 2B to 2C. Indeed, as mentioned above, this was the very main reason why MaaS was initiated in the first way. Integration structure 2C at the level of the trip allows a customer who wants to pay his trip, to use one and the same card for different mobility providers. Stated otherwise, switching between different providers becomes easier. Another significant difference with the pre-MaaS situation is the fact that now, the integration architecture at the level of the mobility provider can be moved from 1B to 2B: when, for instance, a traveler will scan his or her “MaaS transport card”, the devaluation mechanism will (most probably) register a trip and its properties at the level of the mobility provider, which at its turn makes use of another external framework to assure its remuneration, i.e., that of the mobility platform. Remark that at the level of the mobility provider, integration architecture 2B still implies that the connection to the mobility platform is specific for the particular platform one is making use of (e.g., the MaaS mobility provider active in a particular city).

Based on our description of the transition from the pre-MaaS to the post-MaaS era in terms of the different payment integration configurations and the adjoining tables, certain commercial issues currently relevant within the MaaS field can be deducted and put into a modularity integration context. First, as the integration configuration at the level of the trip moves from 2B to 2C, this implies that customers can easily switch from one provider to the other within their subscription. While this increases the comfort level of the passenger and was the intention of the MaaS concept, service providers consider this both as a benefit as well as a potential treat. The flexibility in service provider is generally considered beneficial due to the fact that the mobility platform brings in new customers who can experiment with their services (whereas they otherwise, without the MaaS subscription, might not choose to do so) and therefore increase their revenue. When dividing the competitive landscape between the providers "within" and "outside" the portfolio of the mobility platform, an advantage is typically attributed to the providers within the joint-venture. However, such flexibility may also increase the competition between the service providers within the portfolio. Indeed, as a customer can –within his or her subscription– freely choose between all alternatives (depending on the revenue distribution model adopted by the mobility provider), other providers within the portfolio might become indirect competitors (e.g., customers may switch their preferences towards the usage of shared bikes instead of buses). Currently, most MaaS providers have one mobility provider within their portfolio for each type of transport (i.e., one shared cars provider, one shared bikes provider, etc.). When a mobility platform would one day decide to include multiple providers of the same transport type into its portfolio, fellow portfolio members might even become each others direct competitors. Therefore, some mobility providers advocate the current situation in which their mobility platform only has one provider for each type of service. It is however unclear to which extent platform owners will follow this request as they have created integrations allowing the incorporation of multiple providers of the same service type in a fluent way. Similar competitive dynamics were equally portrayed by Sochor et al. [10]. Second, as the integration configuration at the level of the mobility provider is currently at 2B, this means that, for instance, the card used to register trips is still bound to one specific mobility platform. Using the same card for multiple mobility platforms would clearly further enhance the flexibility provided to the customer, but increase the competition in the platform's market in case multiple mobility mobility platforms would be active in the same region. However, switching this integration from 2B to 2C would provide a more mature modular cross-cutting integration situation, but would (similarly as was the case at the level of the individual mobility service providers), also imply a higher degree of competition for certain players in the market.

In summary we can state that the transition towards a MaaS configuration allows a more mature integration of the remuneration cross-cutting concern in person related logistics as the concern is integrated deep into the modular structure (i.e., until the level of the individual trip) and aggregated via 2B or 2C connections. The exploration of a 2C integration architecture at the level of the mobility provider could contribute to an even more mature modular cross-cutting integration.

As discussed in the beginning of this section, we elaborated mainly on the remuneration concern. However, integration issues in fine-grained service offerings become even more challenging when multiple concerns are considered at once. Consequently, the applicability of our analysis can be expected to increase as the amount of concerns relevant to MaaS increase and the resulting analysis might provide insights to decision takers when confronted with multiple MaaS vendors and parties. As we discussed above in the context of remuneration, platform providers can hold a significant amount of market power by controlling the management of such concerns and many other servitized markets have demonstrated how power over the platform guarantees strong economic returns. Therefore, it can be expected that various service providers will attempt to create initial platforms (as the ones mentioned in the beginning of this section) and continue to enlarge their scope (in terms of revenue and client base, but equally adding and dealing with additional concerns).

B. The Physical Internet

Modularization within the context of transportation is not necessarily limited to the analysis of the vehicles and their load or the service provisioning, but can also be applied at the level of the logistics supply chain. For instance, triggered by the current inefficiencies of most logistics networks (e.g., use of partly empty trucks, suboptimal routes, traffic jams, overusage of highly polluting transportation modes) the *Physical Internet (PI) Initiative* aims to design "an open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces and protocols" [14, p. 152]. In order to achieve this goal, they propose to design a global logistics system based on the basic architectural principles adopted by the Internet for the distribution of digital information. This means that cargo is transported as a set of (smaller) packages, will reach its destination by traveling via a set of connecting nodes, may follow different routes (possibly upfront undetermined) and employs an open infrastructure (public stock facilities or transportation providers) to this end. Related to our focus, it is interesting to observe that the initiators of the project explicitly coin the importance of well-designed modular structures in logistics and the problems associated with the opposite situation: "Innovation is bottlenecked, notably by lack of generic standards and protocols, transparency, modularity and systemic open infrastructure" [15, p. 5].

Whereas the exhaustive analysis of all listed characteristics for this new logistics system is outside the scope and purpose of this paper, some of them can easily be related to our integration pattern analysis presented above. First, regarding the cargo level, it is remarkable that within the PI approach the current freight containers are considered useful, but still too coarse-grained. Instead, a set of unitary and composite π-containers acting as world-standard, smart, green and modular containers is called for. They would differ from the currently used containers by being smaller (causing less "empty space" in containers), (de)composable (allowing to attach or disconnect multiple containers to each other), having advanced securing and sealing possibilities, being equipped with smart sensors and controllers, have conditioning capabilities if required, etc. Stated otherwise, the authors of the initiative argue that one large cargo container is not sufficient and should be considered as a modular system on its own. Of course, the decoupling between cargo and vehicle should be maintained as it was the case for current containers. Therefore, at the vehicle level, vehicles should be manufactured adhering to this new π-container standard. Further, a global Physical Internet could spur the development of vehicles optimized (e.g., using the most adequate integration patterns) for the trajectory that they are required to serve (i.e., in some trajectories external propulsion mechanisms may be present, in others not).

Moreover, the vision of the Physical Internet refers to the logistics network as an additional aggregation level, which supersedes transportation vehicles (i.e., the aggregation level upon which we mainly elaborated in Section III) and needs to be redesigned adhering to modularity guidelines. For example, [15, p. 10] states that logistics networks need to "evolve from point-to-point hub-and-spoke transport to distributed multi-segment intermodal transport". The current logistics networks allow a certain level of intermodal transport, as discussed in Section III-B. For example, a container can be used on multiple modes of transport such as trains, ships, and trucks, without the freight itself being handled. However, the smaller granularity of the cargo as proposed by the Physical Internet will encourage smaller segments and more advanced optimization of these different segments. Once routing decisions can be optimized for a single package, as opposed to an aggregation of packages in a container, advanced algorithms based on the routing algorithms of the digital internet can be leveraged. This vision is in line with our observations based on modularity reasoning on other abstraction levels, but needs to cope with the same practical challenges as discussed earlier. For instance, this vision requires the development of nodes that are highly optimized for load breaking: disassembling aggregations of cargo into individual constituents, calculating the optimal route for each individual π-container, and reassembling new aggregations. As such, these nodes will need to be technologically more advanced than the current logistics hubs.

Many node-to-node segments will still be operated by traditional transportation vehicles, because of the economies of scale of these vehicles. However, because of the small granularity of a single segment and the load breaking capabilities of the nodes, the optimal transportation vehicle can be re-evaluated for each individual segment. Consider the final segment an individual package has to travel in order to reach an individual customer. In certain instances, individual air transport using a drone could be the fastest way to fulfill such a segment. Organizations such as Amazon are already experimenting with this technology, albeit within very strict limitations: the final delivery needs to be very close to an Amazon depot (a traditional hub), and strict weight limitations are enforced. This last limitation relates to the lift concern of air transportation vehicles discussed earlier in Section III-D. Current research demonstrates how this concern can be made scalable without introducing couplings with other concerns, such as drone control [16]. This research shows how cargo can be attached to multiple supporting drones, which, based on force sensing, follow the movement of one primary controlled drone. The primary drone can now be controlled as if it was the sole transport vehicle, albeit with a scalable propulsion concern. This can be considered as an illustration of how state-of-the-art research is able to make advancement towards NST integration patterns previously considered practically impossible. Indeed, NST prescribes that the integration of concerns needs to be solved at the most fine-grained levels, for which several practical obstacles have been identified in the past within the context of air transportation vehicles (cf. supra). The research of Tagliabue et al. [16] demonstrates the practical feasibility of adhering to this principle: a scalable integration of the lift concern at the level of an individual π-container. As such, we believe that further research elaborating on the use of NST as a theoretical underpinning for R&D in the logistics domain would be highly valuable.

V. CONCLUSION

This paper presented an overview of different modular structures that can be identified within the logistics industry. In particular, we studied the alternative integration options regarding the propulsion cross-cutting concern for transportation vehicles (with their associated benefits and drawbacks), using NST as the theoretical basis. We applied a similar reasoning at the level of logistic architectures. Here, we analyzed the integration architecture configurations regarding the remuneration cross-cutting concern within a logistics network. Regarding both the propulsion and the remuneration concern, we observed that the logistics industry already applies a rather mature implementation. However, some suggestions for future research and development could be made based on our theory and it was shown that some recent developments and trends such as the Internet of Things or the use drones seem to facilitate some of these avenues. It is important to stress that none of the authors claim to be transportation or logistics experts. Instead, generally available knowledge within the domain was used as the primary source for the analysis. The main contribution is situated in the fact that we show the applicability and relevance of NST in a context (i.e., transportation and logistics) outside the original application domain of the theory (i.e., software systems). Given our non-expert status in the transportation and logistics domain, we encourage actual experts to scrutinize and validate or refine our initial analyses provided. Additionally, future research could be directed towards the application of a similar analysis regarding the integration of cross-cutting concerns into (physical) artifacts within a particular domain outside the logistics industry.

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