Design and Evaluation of a System of Systems Architecture for the Optimization of a Cyclic Transport Operation

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***Abstract*—Cyclic transport missions involving fleets of vehicles are common in quarry and mining operations and have shown to have a significant potential for energy optimization. Vehicles such as articulated haulers and dump trucks utilized in transport missions can be of different brand, type and have different performance characteristics such as engine power, traction and load. Vehicles may also be operated and owned by different organizations as they can be subcontracted to an operation. The transport operation characteristics include stochastic behaviors and activity times that fluctuate over time, and hence real-time control is required for efficient optimization. As the vehicles are mobile, wireless communication also needs to be available. As the constituent systems (vehicles) have managerial and operational independence, a system of systems approach is applicable. This paper provides an overview of the key characteristics and requirements for such a system and discusses the pros and cons of acknowledged and directed system architectures. Further, a case study is presented where an acknowledged system of systems is implemented in a real world mine and evaluated through a qualitative assessment of an operator assistive optimization system. Key findings include the drawbacks and characteristics of the architecture approaches. Further challenges and potential for automation and production control of a larger process system are described.**

Keywords—System of systems, Transport Optimization, Architecture evaluation

I. Introduction

Cyclic transport operations where a fleet of vehicles share the same mission are common within mining and quarry environments. Vehicles in these conditions are typically earthmoving machines such as articulated haulers or rigid dump trucks. Different earth materials (bulk) need to be moved from one position to another and the total amount of mass to be moved is shared between the machines. Similar situations exist within harbors and terminals (e.g., Ro-Ro) but then not necessarily bulk. Instead, the mission may be to move a large number of containers or trailers. Similar cyclic transport characteristics also exists in other construction operations such as cement production and the road asphalt construction processes.

The fleet of vehicles used may for different reasons not consist of the same type, brand and age. From case study observations, we know that the fleet may also consist of vehicles owned by different contractors. How the operation is governed varies in between enterprises and sites. Some sites own and operate their own fleets, but in some cases the fleet of vehicles used is subcontracted or bought as a service. When machines break down, additional machines may be requested on short notice from different subcontractors. The vehicles thus exhibit some degree of both operational and managerial independence, and it thus makes sense to regard this as a system of systems (SoS) problem [1].

A. *Process characteristics*

Research has shown that transport operations in quarry and mining has a large potential in productivity and energy real-time optimization since large operational waste is common [2]. The operation is hard to schedule and design perfectly and machines are discrete entities. If the absolute need of capacity is, e.g., 1.3 vehicles the operation management will need to choose one or two vehicles. This results in either one vehicle having too little capacity and the transport becomes the bottleneck of the overall process, or in two vehicles with 0.7 vehicles in transport overcapacity.

An additional complicating factor for quarries and mines is that the operation often changes over time, where the mission configuration, including destinations, distance and route, varies. In observed case studies, this sometimes happens even within the same work shift. In addition to the mission configuration changes, the operational activity characteristics in time and capacity are stochastically changing. Activities such as loading time and absolute load amount, both in weight and volume, often change which affects the productivity capacity, ton/hour.

B. *Communication challenges*

Research has shown that the additional capacity results in waiting at the bottleneck while optimization could save energy and costs for the operation [3]. As the operations are stochastically changing and involve a large amount of optimization variables, it cannot be assumed to be effectively scheduled in advance. It requires a continuous control system and as the constituent systems are mobile, availability of wireless communication is a key factor.

Quarries and mines are often remotely located where few humans live or visit. Countries with extensive mining operations include India, Australia, Brazil, Russia, Canada and China. These are all large countries with considerable amounts of remote areas. Mines are usually either underground or in a deep pit surrounded by solid rock material. Standard telecom networks as connectivity infrastructure coverage may either be too weak or not available which makes it unreliable for the need of continuous real-time communication-based applications. Some mines build their own communication infrastructure, but this is still not a common approach that covers the whole site.

An additional factor that complicates the construction and maintenance of connectivity infrastructure is that the operation expands continuously, often through blasting activities. This makes the continuous configuration of infrastructure, including its energy supply, challenging to maintain.

C. *Contribution and overview of paper*

The contribution of this paper is the assessment of SoS architectural patterns as a basis for the design of the optimization system for transport missions in quarry and mining operations. The following section discusses the control system required and how the location of the functions is affected by the different architectural patterns [4]. We assess the pros and cons of the different architectural patterns and present a candidate solution. The solution is implemented, tested and validated through a prototype in simulations and in a real world mine case study operation. Finally, suggestions for further research and activities are presented.

II. OPTIMIZATION CONTROL SYSTEM

The overall aim of the transport operation is to transport mass as efficiently as possible over time. The capacity limit is defined by the process bottleneck. While the mission, the operative capacity or other production targets are defined and obtained, the operative optimization potential is to minimize efforts for the same. While the machine fleet, route and operators are given, the effort to optimize is energy consumed.

As the activity times in the cyclic operation fluctuate stochastically and continuously, a fixed optimal schedule for the vehicle activities is not expected to be useful. Instead, a real-time optimization system that continuously monitors and responds to changes and perform relevant adjustments to the fleet operation is required. In addition, the fleet configuration needs to be continuously updated as vehicles instantly can be added or removed from the transport mission.

The coordination of the machines includes several coordination use cases [5]. With lean thinking the overall mission can be described as performing a certain production, e.g., units or mass moved within a time frame. This description can be measured in ton/h or units/h moved from origin to destination. But the mean productivity may not be accurate in instantaneous time as time often is required for setup and startup of the operation. Manual operation often requires breaks for the operators, machine failures, and operational events such as moving the loading machine also cause an instantaneous break.

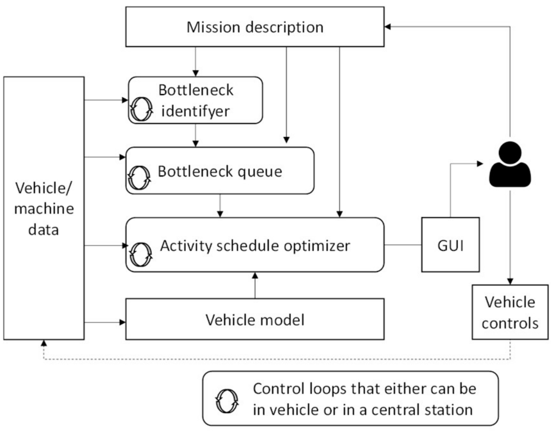

Fig. 1. Optimization control layers and operator interfaces.

While the mission is divided into several activities, the activity with the lowest capacity (i.e., the bottleneck) defines the maximum productivity available. For the other activities the minimum energy consumed can be optimized towards the productivity of the bottleneck activity.

To optimize the operation without losing production, different levels of control is required. First is the common view of which activity constitutes the bottleneck to optimize towards. This control loop needs to continuously measure the capacity available for each activity and define where the least capacity is obtained. In normal operation the bottleneck will be preceded with waiting time. The second level needs to queue up the order for which vehicles will reach the bottleneck. The timeslot for a vehicle to optimize towards can be defined as the time when the bottleneck is available to the activity. This can be defined as the time when the vehicle ahead in the queue leaves the bottleneck, and it can be predicted combining historical and current data. When the time of arrival to the bottleneck is defined, a model for energy minimization to perform the activities prior to the bottleneck can be utilized. Different models for energy consumption may be applicable for each vehicle and activity as, e.g., loading, transporting with load, and return trips without load may all have different characteristics and variables to consider for the optimization calculations to reach bottleneck just in time (JIT) with minimum energy consumed.

The control system required for lean optimization, see Fig. 1, consists of three control loops that consume vehicle data for its internal algorithms and a coordinating system that provides the transport mission and configuration. The transport mission description and assignment of fleet to the mission can be assumed to come from a higher-level process as described in [6]. The control loops consume vehicle and machine data and require an accurate vehicle model to optimize towards the throughput. In more detail, the modules can be described as:

- *Mission description*: A mission needs to include the origin of goods items/mass, the destination and a target of the amount of goods or mass over a time period.
- *Bottleneck identifier*: In a lean philosophy the process can be described with its activities, e.g., receive load, transport load, unload and return transport. One of these activities is always the bottleneck. The bottleneck activity needs to be identified and optimized towards. As the bottleneck may change over time a continuous identification is needed. The agents in the system must have the same view of where the bottleneck is, as the subprocesses will need to optimize towards the bottleneck to maximize its throughput.
- *Bottleneck queue*: As the operation is physical, two machines cannot be in the same place simultaneously, and for this reason a scheduled queue of the bottleneck is needed. If the loading is the bottleneck, the ordered schedule of the approaching vehicles is required which provides a target time of arrival for each vehicle to optimize towards. As the operation fluctuates, the target time of arrival can be expected to change instantly and continuously.
- *Activity schedule optimizer*: To reach the bottleneck activity just in time (JIT), a schedule of the remaining

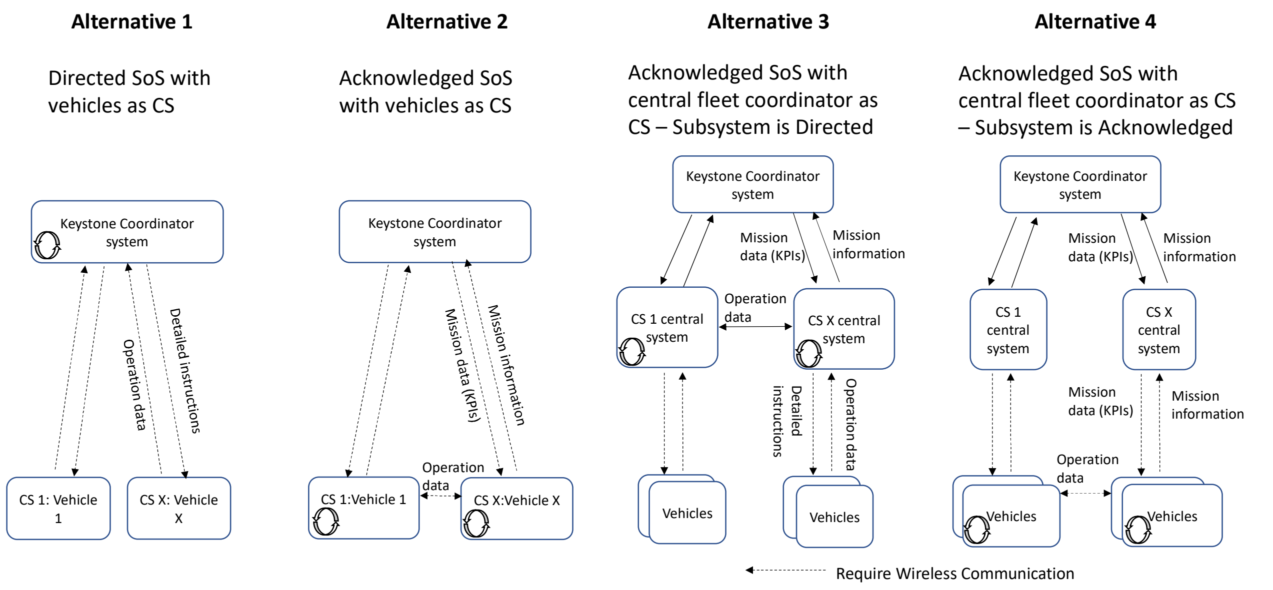

Fig. 2. SoS archetypes and information levels for mission optimization.

activities for each vehicle to reach the bottleneck is required. The activity schedule optimizer utilizes the activity timings and route and map data as well as a reliable vehicle model to predict and plan the schedule towards reaching the bottleneck JIT.

- *Vehicle model*: A vehicle model can be static as long as it is accurate and reliable. However, as dynamic variables including weather, working temperature, traction, load, topography and route are expected to influence, a model is suggested to be based on continuous machine learning algorithms with up-to-date vehicle and environment data. As the optimization target is to fulfill needed production with minimum efforts, the energy consumption needs to be the dependent variable of the model.

- *Vehicle data*: Vehicle or machine data includes data from all relevant vehicles in the operation. Parameters such as time, position, speed, weight of load, roll, pitch, altitude and temperature are foreseen significant variables to utilize in the optimization and control modules.

While the control loops in each layer is required in a functional architecture, they can be distributed to a physical architecture in different ways. In the alternatives presented and assessed, the control loops are either in the vehicle or in central system, see Fig. 2.

As the functional performance of the optimization is expected to be fulfilled independently of architectural pattern the design assessment will consider the non-functional aspects. The following chapter orchestrate [7] and assess SoS alternatives utilizing the different architectural design patterns.

III. Architecture Design

A traditional approach to this optimization problem is a centralized coordinator with optimization algorithms that in detail instruct the vehicles and their operators on the desired behavior including speed profile for the vehicle to follow. The central coordinator thus orchestrates the operation of the SoS. When the schedule is predictable or when sufficient wireless communication is available this approach is feasible. When the behavior is stochastic with continuous changes the behavior updates need to be continuous which requires an available and reliable connectivity.

An alternative solution to this approach is a decentralized optimization architecture where the agent optimizes its own operation based on a common view of the mission and situation. This is a choreography-based approach, which reduces the requirement on intelligence and dependency of the central coordinator as the short cycle loops are within the vehicles. To model and describe the differences, the SoS archetypes suggested by Maier [1] and Dahmann et al. [8] can be used.

Independently of SoS archetype we assume that the data abstraction level for the communication interface needs to be at least on the semantic level [9] due to the required common control characteristics. Data Level Integration is suggested to be based on message exchange [10], which allows for a loose coupling. The message exchange that is required in an acknowledged SoS needs to contain the needed operational data to ensure a common view of where the bottleneck is, how the queue is defined and organized, and principles for how the scheduling is performed.

In a centralized approach, described as a directed SoS, Alternative 1 in Fig. 2, a schedule can be continuously updated while sensors monitor key activities and deviations. The architecture is dependent on data from all vehicles (CS) being continuously updated with status and behavior, including position, speed, load etc. Changes in the schedule can then be communicated to the vehicles with directions on how to operate the vehicle effectively, which can include destination, route, speed profile, etc. The directions can either be on the detailed level where a specific route and speed profile is communicated or on the more abstract level where destinations with time intervals are communicated for a vehicle internal system to calculate the route and speed profile. While referring to the logical levels in Fig. 1, all the middle layers are implanted in a central coordinator in Alternative 1.

A different approach is that a central system only distributes the overall mission instructions to the machines and let them manage the real-time coordination. This is only the mission description logic in Fig. 1. This architectural approach can be described as an acknowledged SoS. An overall mission including the destinations and activities that are required are transferred to the vehicles, and the only follow up from the vehicles is on mission progress (e.g., KPI:s). This requires that the vehicles instead receive the activity data from the other vehicles within the same mission and possibly from the loader and unloading station (if there are constraints).

The first two alternatives are based on that Vehicles are CS. An alternative to this approach is that a fleet of vehicles is connected to a central system cloud, which could be provided by the vehicle manufacturer (OEM). In this case the cloud service is a CS and can include several vehicles in the fleet. In alternatives 3 and 4, CS are part of an acknowledged overall archetype, but the role and level of operative coordination and optimization are different. Alternative 3 defines a real-time interface in-between clouds for coordination and optimization. Alternative 4 utilizes the same coordination as alternative 2 where the detailed data used for coordination is exchanged in-between vehicles and the logic for optimization resides within the vehicles [5]. The communication channel for operational data can utilize infrastructure for relaying data over long distances but the SW consuming data is distributed to on-board control units in the vehicles. The common mission will come from a coordinator system. As an SoS this can be considered as an Acknowledged archetype.

IV. Architecture Assessment

To assess the different architectural patterns, we use non-functional aspects that have shown, or is expected to have, significant impact, based mainly on the definitions in [11]:

- *Reliability* emphasizes the ability of the system to function without failure. A failure can be caused by a lot of different reasons. In this case we focus on the main differences in the architecture which is mainly the location of software modules which are depending on wireless communication. In a distributed architecture as the acknowledged type, the system is less sensitive towards failures in central systems which makes the system architecture by design more reliable.
- *Availability* emphasizes the ability of the system to operate satisfactory at a given point in time. While all the architecture alternatives utilize vehicles and require embedded solutions, these components can be assumed to have similar availability independently of architecture. While putting logic in the vehicles, less dependency on central systems emerges. As less complexity and fewer components are involved, the availability of the system can be assumed to be higher with the optimization logic in the vehicles.
- *Scalability* can be described as the ability to handle a growing workload or increased scope while, e.g., additional resources are added, or updated complex algorithms are required. Central IT systems have an advantage over embedded systems for scaling SW. Embedded does not scale indefinitely as it has physical constraints in the vehicle. For this reason, the central system has an advantage when unpredicted significant scaling is required.
- *Security* describes the protection of the system towards malicious attacks. A vehicle that is exposed to external systems directly is more exposed than vehicles that are privately connected to a trusted central system controller by the OEM. If the OEM system provides certificates to reliable sources more security risks are managed.
- *Maintainability* is the ability to identify, diagnose and correct defects or faults. As long as system diagnostics exist independently of SW location, there should not be any differences between the architectures. However, as the centralized system requires a communication infrastructure, the response time while errors are detected will be assured. But this is an option also for the decentralized architectures as it does not rule out reliable central communication, only becomes less dependent on it.
- *Usability* describes the degree to which the system can be used by users to achieve specified goals. The user interface is a challenge, but as there are no differences expected depending on architecture pattern, the alternatives is assessed as equal.
- *Serviceability* describes the ability to install, configure and monitor systems. An increased decentralization and interoperability also increases the complexity of serviceability. What is important in this context is that the control objectives and overall rules are common. The vehicles need to have a common view of how to interpret information about destinations, activities, bottlenecks, and time of arrival. For a multi-vendor vehicle interoperable approach, common standards defining the behavior of the logic and communication protocols are required.
- *Compatibility* and interoperability are the system characteristic where interfaces are completely understood for its purpose. Independently of SoS pattern the design must fulfill this and relevant standards are required. For this reason, we assess them to be equally challenging and independently of choice, standards are lacking.
- *Life cycle cost* is the total cost of ownership over the life of the system. As the dependency on central communication require more advanced components, installation and maintenance the architectures where the optimization algorithms are placed centrally are assumed to have a higher life cycle cost.

In Table I, we summarize the alternatives in a Pugh matrix [12]. As the solution domain can be considered as a greenfield [4], we choose to use alterative 1 as baseline and assess the other alternatives towards this solution. In the table -1 is worse, - is same and +1 is better. We have weighted the different criteria's equally. A different weighting or including other criteria may change the outcome. Assumptions made in the analysis influence the results. The outcome of the architecture assessment shows that Alternative 4 is the best candidate to use.

TABLE I. SOS ARCHITECTURE ASSESSMENT SUMMARY

Criteria	Baseline	Alternatives		
	Alt. 1	*Alt. 2*	*Alt. 3*	*Alt. 4*
Reliability	-	+1	-	+1
Availability	-	+1	-	+1
Scalability	-	-1	-	-1
Security	-	-	+1	+1
Maintainability	-	-	+1	+1
Usability	-	-	-	-
Serviceabiltiy	-	-	-	-
Compatibility	-	-	-	-
Cost	-	+1	-1	+1
Total		+2	+1	+4

V. VALIDATION

To validate the suggested approach a prototype system was developed. The prototype HW architecture and communication strategy is described and implemented in [13]. The results from the tests showed a significant fuel reduction.

The prototype utilizes a 7-inch screen as GUI that was mounted on the dashboard in the vehicles. The GUI was used by the operators of the vehicle to configure the mission. It also presented driver feedback including the map, vehicle positions, route as well as current optimal lean speed. Once an operator has configured a mission it is broadcasted so that the others can chose to be part of the same mission. The central optimization algorithms for Bottleneck identifier, Bottleneck queue and Activity schedule optimizer were located in the embedded prototype unit mounted in the vehicles. The communication used was 802.11p and the wireless communication characteristics and limitations are presented in [14]. The time of arrival optimization logic is described in [5].

The system functionality was tested and verified in a realistic transport mission scenario utilizing real machines and real material to transport. The system performed as expected and significant energy consumptions was achieved without lowering throughput [13].

A pilot in a real world mine was also performed for validation purposes during live operations. However, as the mine changed mission operation, fleet configuration, destination and route continuously, the manual configuration of missions was not sufficient. The optimization requires all vehicles in the fleet to be part of the system. If there are vehicles that take part in the work but are not connected to the system, it adds a significant disturbance. Further the pilot site had a complicated topography with lots of obstructed areas over a distance of 1.3 km, which caused the connectivity to work insufficiently. For the site utilized in the pilot trials, an infrastructure consisting of base stations for at least relaying the messages at some location would be needed. Unfortunately, this was not available in the pilot test. For quantified validation purposes the study relies on the validation done in simulations and shares the findings of system requirements from the pilot assessment.

To complement the study when it comes to operator usability, a qualitative assessment thorough an anonymous questionnaire was made where the eight human drivers of the hauling vehicles in the real world mine were asked to assess the system tested. Six drivers agreed and two were neutral to that the system was useful and seven agreed and one was neutral to that the speed advice was easy to follow.

VI. DISCUSSION

While the assessment presented is based on an overall requirement perspective small changes can change the outcome. The authors acknowledge that different sites have different preconditions which influence the requirements. One such condition is the availability of wireless connectivity. Some sites have a well-developed infrastructure, and some do not. While the former can choose architecture based on other criteria, the later benefits from decentralized solutions compared to larger investments in purchasing and maintaining such infrastructure. Further research could investigate a hybrid solution that allows for a combination of the alternatives in the system.

As security and safety of vehicles are important aspects for all OEM:s, we do not foresee that the vehicles will have a direct external interface for control without the involvement of a central backbone providing certificates and facilitating the communication. The VANET developments including 808.11p standards allow decentralized communication to take place with a security mechanism that is based on central updates. Such communication can be an alternative solution for the local communication. Cellular technologies are developing with e.g., edge computing and network slicing technologies which intend to increase performance, availability and reliability of the network. It is also an option to consider. The tests performed in the study utilize proprietary protocols to communicate in between vehicles to ensure that the control system utilizes the latest data from the operation. For an SoS this protocol needs to be standardized for which there are no currently known initiatives available.

While considering a larger operation such as road construction, there usually exist several sequential cyclic transport processes. These can be controlled and balanced on a higher level, and for this purpose further research is required to build the overall SoS. The intention with the SoS presented is to be part of, and deliver value to, the larger system perspective simultaneously as it increases effectiveness and productivity in its own subprocess. This hierarchical arrangement is discussed further in [6].

The implemented prototypes that were utilized in the tests include an advisory speed for the drivers and operators of the machines and vehicles. In a driverless operation the interface will be to a direct control system. It is worth noting that such an automated solution would require much more detailed descriptions of, e.g., missions, since there is no human operator that can fill in the information gaps based on common sense and experience.

VII. RELATED WORK

The approach presented is similar to the green light optimal speed advisory (GLOSA) application where traffic lights signal their phase and timing information to vehicles [15]. The information is then utilized by approaching vehicles to e.g., adapt its speeds to an optimum for the intersection of interest. In the presented case each vehicle instead needs to adapt its speed to reach the bottleneck as the bottleneck should not have any downtime. The vehicle aims to reach the time slot for the bottleneck activity and considers the available traffic and other activities required to reach the bottleneck JIT.

From a process optimization perspective there is a large field of research that tackles the site planning and fleet configuration aspects as presented in [16]. Additionally, there are lots of work on individual vehicle optimizations as e.g., gear selections [17]. However, there is a lack in lean real-time optimization of the cyclic transport operations including a fleet of vehicles, which is addressed in this paper.

Within quarrying and mining there is related work to optimize other subprocesses as the crusher and feeding processes, but the cyclic transport operation is excluded [18].

Dadhich et al. [19] present key challenges for automation of earthmoving machines and explicitly define the transport operation as a promising area for automation but also conclude that the loading procedure is expected to be manual in a foreseeable future. While the transport vehicles become autonomous the need for operation control is increased. Further the introduction of autonomous vehicles is expected to introduce increased need of central control, a.k.a. Control Towers. These systems are expected to increase the need of SoS design and standards for co-existence and co-operation of autonomous vehicles.

An investigation of architecture alternatives for cyber-physical systems, with parts of the functionality allocated in embedded systems or as cloud services, was reported in [20], showing similar advantages of the cloud as in this paper.

VIII. Conclusions

We have presented the control logic for a lean based optimization of a cyclic transport operation for quarry and mining processes. We have discussed and assessed how the control logic can fulfill utility through the functionality required by different SoS archetypes, and design patterns.

Based on the architectural assessment and validation we suggest an acknowledged SoS architecture design with centralized constituent systems with an acknowledged design as presented in alternative 4 in Fig. 2.

We have discussed pros and cons while considering the non-functional aspects. We conclude that there does not exist a “one type suits all” architecture. Instead, different specific sites and enterprise conditions and preferences can influence the assessment, and the SoS architecture needs to include variability points to adapt to the situation at hand.

We have implemented and tested a decentralized architecture and verified that its functions work and can save energy for simpler workflows. We have also, through a qualitative assessment, assessed the drivers’ view on the usability of the prototype system.

We have also identified that the implementation requires flexibility for complex operation where key variables change continuously. While the operation covers larger geographical areas, some communication support infrastructure is needed even in a decentralized architecture. We also learned that while an operation includes several destinations as can happen when a loader decides destination based on loaded material, the loader must be in the system and define the specific vehicle mission. Other constraints can be that an unloading position includes constraints such as a crusher always requiring a certain minimum amount of material in its buffer.

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