Towards a System-of-Systems for Improved Road Construction Efficiency Using Lean and Industry 4.0

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***Abstract*—Road construction is a very large business segment, consuming enormous public funding every year and with significant environmental impacts. However, the rate of efficiency improvement during the last few decades has been negligible, whereas other industries, such as manufacturing, have seen very large improvements by applying automation and Lean-based flow optimization across the production system. In this paper, we outline a system-of-systems concept for road construction which applies similar principles as have previously proved successful in other industries. The paper identifies efficiency attributes and wastes in current practices, which lead to a conceptual solution that focuses on improved coordination of working machines. Technical elements from Industry 4.0 are considered as potential building blocks in this concept, identifying similarities and differences between the construction domain and other industries. Finally, challenges are identified, in particular within knowledge representation and information management.**

Keywords—System-of-systems; Road construction; Lean; Industry 4.0; Architecture.

I. INTRODUCTION

The construction sector is one of the largest industries in the world, with an annual global turn-over of around $10 trillion, or 13% of the global GDP [1]. Construction activities include buildings, roads, railways, power and communication infrastructure, water and sewage, and a broad range of specialized activities. The construction industry also has significant environmental impact, and it has been estimated that as much as 5-10% of the total greenhouse gas emissions in the transport sector stem from road construction [2].

Many other industries, such as manufacturing, have worked systematically with improving their efficiency using automation, standardization of material and processes, process flow optimizations, etc. This has led to annual improvements in productivity in the order of 3.6% over the last 20 years [1]. At the same time, the construction industry has remained labor intensive and uses specially crafted solutions, leading to an improvement of only 1% per year during the same period [1].

In our research, we are making the hypothesis that better communication and coordination between the parties involved in a construction endeavor would have substantial positive effects on productivity. Since there are many independent systems involved, this turns into a system-of-systems (SoS) problem [3]. The overall purpose of this paper is to investigate a general SoS concept that can address some of the challenges related to productivity and environmental impact that the construction industry faces, and that can be applied across a wide range of projects. The intention is to create a platform within which it is possible to iteratively improve efficiency over time.

In this paper, the focus is on road construction. This is an important subdomain of construction, which involves primarily earth moving machinery. Many of the problems related to road construction also exist when building other important infrastructure such as railways and airport runways. To give an indication about the size of this industry, Sweden spends around 1% of its GDP on road and railway construction [4].

A. Research Questions and Method

The research questions studied in this paper relate to the purpose of finding an SoS concept for improving road construction efficiency. Specifically, the following questions are addressed:

1. What are the key information-related improvement potentials in road construction?
2. What is a suitable SoS concept to realize those potentials?
3. What techniques from manufacturing can be used in such an SoS concept?

Since this research is constructive, in the sense that the ultimate objective is an artifact in the form of an SoS concept, a research method based on Design Science is suitable [5]. In this method, the desired artifacts are developed and evaluated in an iterative process, where the evaluation is based on both interacting with the relevant environment and with the existing knowledge base. The interactions with the environment are particularly important and have primarily consisted of workshops with road construction specialists to get a deeper understanding of the process of building a road, as well as into the potential improvements. Also, existing descriptions of road construction activities, both publicly available and company internal, have been studied.

B. Overview of Paper

The remainder of this paper is structured as follows: In the next section, an overview of road construction is given, together with some qualities that define efficiency. Also,

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potential wastes are identified based on the seven Lean waste categories, leading to some concerns for the solutions. It is then investigated in Section III how technologies used in other industries can be applied, and some differences and challenges to construction are identified. In Section IV, a concept that addresses the concerns, partly using the existing building blocks, is described. In Section V, some related research is reviewed, and in the last section, conclusions are summarized together with plans for future investigations and refinements.

II. Efficiency and Wastes in Road Construction

We will now analyze the road construction activities to understand where improvements can be found. First, a summary of the process is given, and what actors are involved. Then, the qualities to optimize are described. Finally, an analysis of potential wastes using Lean principles is described.

A. *Road Construction*

An overview of the basic steps of the road construction process will now be given, see Fig. 1. Although there is a very important planning and tender process before construction starts, the focus here will be on the actual building of the road.

The road consists of several different layers, as illustrated in Fig. 2. As a first step, the sub-grade is prepared by removing or adding earth material and rocks to provide a stable level surface on which the road will run. Then, a sub-base is put in place using aggregate (i.e., crushed stone), usually in several layers with gradually smaller sized stones. Then a base layer is applied, where the stone material is bound by asphalt, bitumen or concrete. Finally, the wearing course layer of asphalt is added. The purpose of the multiple layers is to distribute the weight of the traffic to minimize the risk of road damage. Typically, 1 m^2 of road requires 2-3 tons of rock material.

Aggregate material is a key component in the road, and this can be supplied either from a quarry or by reusing rocks that need to be removed when preparing the sub-grade of the road. In either case, the process is to blast the rock using explosives; load the resulting stones onto a hauler; transport the stones to a crusher; screen the crushed stones based on size and quality; load it on a hauler; transport it to the road and off-load it; level it on the road using a grader; and packing it using a compactor. This is repeated in multiple iterations adding layer by layer. Often, material is stockpiled at various stages of the process to cope with varying production rates of machinery.

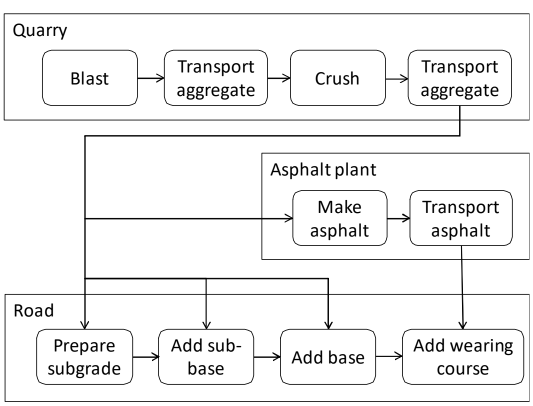

Fig. 1. Overview of road construction processes.

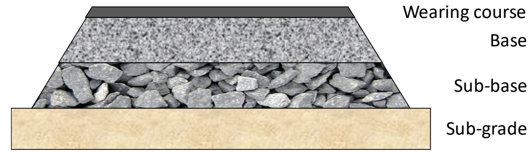

Fig. 2. Road layers.

For the asphalt part, aggregate material is transported from the crusher to an asphalt plant, where it is mixed with bitumen. The hot and viscous asphalt is loaded onto dump trucks, which transport it to the road, where it is off-loaded into a paver which spreads it out, before compacting it with a roller.

The above description outlines the generic steps in a road construction process. However, it is important to notice that there are very large differences between various road projects, depending on the circumstances. This is a difference from manufacturing, where the same factory produces identical copies of a product again and again. Apart from the steps described here, there are also other work items, such as building bridges and tunnels, putting up markers, etc. that will not be considered further in this research.

B. *Actors*

In most road construction projects, a number of organizations participate and form a decision hierarchy. At the top is the customer in the form of the future road owner, who can either be a public road authority or a private company. The customer decides on the overall characteristics of the road, and then initiates a tender process to select a contractor. This contractor takes the overall responsibility for delivering on the customer's specification, but normally uses a broad range of suppliers and sub-contractors in the process. This includes suppliers of material as well as of equipment, the latter coming directly from a construction equipment OEM or through a rental service. There is also a financer, which can be a private company, a public agency or a public-private partnership.

C. *Qualities*

From the perspective of the customer, the overall specification of the road should be fulfilled by the contractor. In this, the following qualities are usually central:

1) Total cost: The main categories include material (e.g., asphalt, aggregate, fuel, water, concrete); equipment; wages.

2) Timeliness: The road is to be finished within a given time frame, according to a master plan developed by the owner. Delays often result in fines and added cost for the contractor.

3) Quality: This can include smoothness of the road, its profile, and how well it can support traffic loads over time. Poor quality can lead to rework and added costs.

4) Environment: Apart from the already mentioned green house gases from transportation at the construction site and for material logistics to it, the production of asphalt produces further emissions. There can also be effects on ground water, disturbances from noise and vibrations, and effects of chemicals used. A road construction project is often subject to approval and constraint by environmental protection agencies.

5) Safety: The risk of accidents for workers at the site must be minimized, and also their exposure to dust, noise, and emissions. Further, risks to the general public need to be handled, in particular when construction is carried out in connection to an existing road with traffic.

For a contractor, the goal is at first to win the contract, by bidding a sufficiently low price. Once selected, the goal is to deliver the specified road at a minimum cost, which means productivity must be optimized.

D. Wastes

To see how the qualities can be improved, we will follow the example from manufacturing and use Lean principles originating from the Toyota Production System. These principles include the identification of seven types of wastes [6], where a waste is anything that does not add value and can be expressed in some of the qualities presented in the previous subsection. It will now briefly be described how those waste categories appear in road construction, and ideas for reducing them based on improved communication and coordination.

1) Overproduction: Producing faster or in greater quantity than the customer demands does not add value. It is caused by a failure to balance supply to demand, such as large batch sizes; unreliable processes; unstable schedules; unbalanced work stations; working on forecasts and inaccurate information rather than actual demand. *Example*: Blasting and crushing more aggregate than needed. *Solution*: Use a pull (kanban) system instead of push, which requires communication between the producer and consumer.

2) Waiting: Unused machines or workers, or goods not being worked on, do not add value. It is caused by a failure to synchroize activities, such as operators waiting while machines cycle; long changeovers; unreliable processes or quality; batch completion rather than single piece transfer between operations; time to perform rework. *Example*: Haulers waiting to unload to a crusher; trucks waiting to fill the asphalt paver. *Solution*: Communication of required time of arrival allows the vehicles to optimize their traveling speed, and potentially also to remove vehicles. Automate certain machines, such as asphalt compactors, to remove operators.

3) Transportation: Unnecessary movement of people or material **between** processes. It is caused by poor layouts with large distances between operations; large batch sizes; multiple storage locations. *Example:* Aggregates being fetched from a quarry far away; using central rather than local stock-piling areas; removing earth material that could be used as part of the construction. *Solution:* Higher precision in the information about the workplace can allow better planning.

4) Overprocessing: Processing beyond the standard required by the customer can occur as a pre-caution, which is due to insufficient information, such as lack of standardization of best techniques, unclear specifications or quality standards. *Example:* Using unnecessarily much aggregate; doing more compacting than needed. *Solution*: Improved measurements of work status; clearer information about required standard.

5) Unnecessary inventory: Storing raw material, work in process, or finished goods wastes space and effort. It is caused by lack of balance in work flows; large batch sizes; long changeover times. Sometimes, it leads to scrapping of stagnant material that stays in inventory for a long time. *Example*: Crushing is done before road construction starts; aggregate in stock-piling gets segregated in different particle sizes. *Solution*: Use communication to balance supply and demand.

6) Unnecessary motion: Unnecessary motion of people, material or machines **within** a process. It is caused by poor workstation layout, transfer of material, large batch sizes, reorientation of material. *Example:* A wheel loader feeding a crusher may need to move excessively due to poor layout. *Solution:* By collecting information of movements, layout improvements can be identified.

7) Defects: Rework may be needed if sufficient quality is not achieved. It is caused by unclear operating procedures; unclear specification; inadequate training; incapable processes; incapable suppliers; operator errors; etc. *Example:* If the material or compacting is inadquate, ground frost may cause damage, which needs to be repaired. *Solution:* Improved measurements of work status; clearer information about required standard.

E. Concept Concerns

The overall purpose of the SoS is to improve qualities by reducing wastes through the usage of improved communication, coordination, and information. However, apart from this overarching functional need, there are a number of other concerns that also need to be addressed by the concept:

- *Multi-vendor*. Any large construction site employs machines, IT, and communication systems from different vendors, so the concept must be open to their usage as well, and hence industry standards should be applied when possible. This also means that existing machines should be possible to adapt to become SoS constituents.
- *Autonomous and manual*. Over time, machine automation will increase, and the concept should allow different degrees of machine autonomy to be used. However, manually operated machines will remain in use for a long time, so the concept also needs to be able to connect to the machine through its operator.
- *Secure*. Participating in an SoS requires a certain degree of openness, and it must be ensured that the communication interfaces do not allow manipulation. It must also be assured that confidential information of a certain participant does not become accessible to others.

- *Flexible*. A difference between road construction and manufacturing is the continuous changes in the former. The process has much shorter periods of steady state, which makes process optimization more difficult. This increases the need for up-to-date information, support for re-planning and reconfiguration. The variability between different construction projects is substantial.
- *Robust*. It cannot be assumed that communication is reliable all the time, since road construction must rely on wireless communication, and the coverage of cellular networks is often poor. Therefore, solutions need to be able to recover from communication outages.

III. Industry 4.0 Building Blocks

Since the comparison to manufacturing industry is so unfavorable for the construction industry, it makes sense to look at the latest and greatest technology from that domain, in order to catch up. The current development in manufacturing is focused on the usage of Internet of Things technology to increase connectivity, and this concept is called Industry 4.0 (I4.0) in Germany [7]. Similar ideas are being pursued elsewhere under different names, e.g., Industrial Internet in the US. In this section, some key technologies from I4.0 will be reviewed, as potential building blocks of the SoS concept for road construction. Note that many of the concepts of I4.0 are still under definition and have not yet been standardized.

A. Reference Architecture

One of the major results of I4.0 is the establishment of a *Reference Architecture Model for Industry 4.0* (RAMI4.0), which is a three-dimensional framework for the manufacturing domain [8]. The three dimensions are:

1) Layers. This dimension represents the IT structure of production. As a general principle, information exchange should only occur within layers or between adjacent layers. The following layers are included, from the top and down:

- *Business*: Represents the overall business processes and orchestrates the functional layer.
- *Functional*: Contains rules and decision-making logic.
- *Information*: Provides data persistence and integrity, processes events from lower layers into data of different abstraction levels.
- *Communication*: Standardizes data formats to be used towards higher layers, and control services.
- *Integration*: Provides the interface between the physical reality and the IT systems, with information about the assets and events. Also includes Human Machine Interfaces (HMI).
- *Asset*: The physical reality, including humans.

2) Life Cycle & Value Stream. In this dimension, a clear distinction is made between type and instance, where the former refers to the description of a product, and the latter to the individual copies of it. The type is thus relevant for product development, whereas the instances come from the manufacturing which uses the type description. However, there is also a feedback loop that takes data gathered from production into development, allowing improvement.

3) Hierarchy. This dimension provides a functional hierarchy describing the responsibilities of different levels. It is based on a traditional automation industry hierarchy of enterprise, work centers, stations, and control and field devices, but adds to that at the top a link to the connected world outside the factory, and at the bottom makes the product explicit, since it may nowadays also contain some functionality during production.

B. Component Model

To allow different assets to be combined into a system, the integration layer provides a uniform way of connecting the physical assets into the cyber-world. This is called the *asset administration shell* (AAS) [9], and it provides the API for a number of services that all assets should provide. They include identification, configuration, condition monitoring, events, etc.

The shell consists of a header and a body, where the header contains identifying information about the shell and its asset, captured in a manifest, i.e., a self-description. The body provides domain-specific sub-models, and these are handled through a component manager.

There is also an interaction manager responsible for processing communication with other components, and this is done based on a domain-independent basic ontology, which the shell then can map into its own domain-dependent ontology. The shell may thus implement parts of the information layer of RAMI4.0, but other parts may be kept in other IT systems.

At a functional level, the asset's functions or capabilities are described in a standardized way. This includes the properties of the function (e.g., type, parameters), and its input and output variables. Assets may also be grouped hierarchically, so that a set of assets may be given a common administration shell. The same asset can also have several shells, for different purposes.

C. Communication

As a foundation for communication, I4.0 utilizes an existing and well-established standard called Open Platform Communications Unified Architecture (OPC UA) [10][11]. It primarily uses a service-oriented architecture based on client-server communication, although a recent extension also allows publish-subscribe message brokers such as AMQP [12].

Key services include real-time data access, alarms and events, and historical data access. Data is represented using XML but can also be encoded in a binary format to increase performance. The information model is a tree-based hierarchy, where the nodes can represent structured objects or variables for dynamic data. The specification is open-ended, with generic data access mechanisms that do not specify the domain-specific content of data, such as which variables or objects to use.

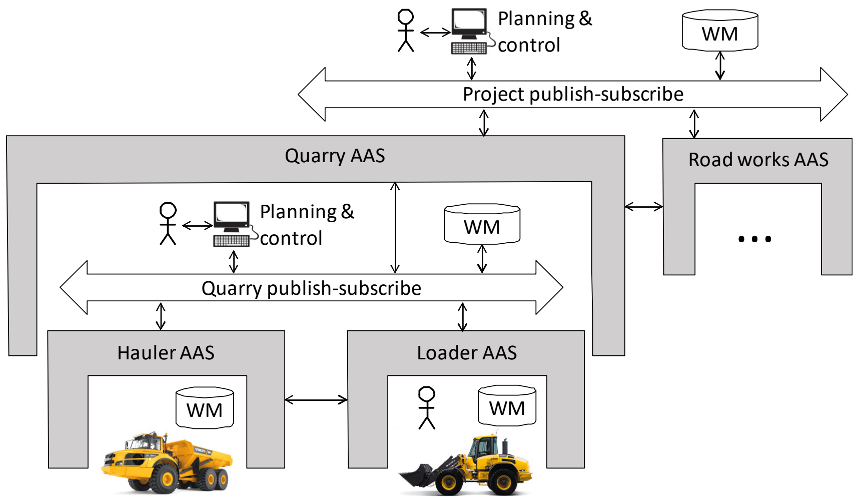

Fig. 3. Hierarchical decomposition of a road construction SoS.

D. *Security*

Security is regarded as an important property in industrial automation, partly because lack of it may lead to safety risks in the physical environment, but increasingly also for guarding confidential product information [13]. Parts of the technical solutions are available through OPC UA [10], and includes mechanisms for authentication and authorization, encryption, etc. In addition, a number of management and organizational mechanisms are suggested [14].

IV. Concept Description

We will now present an initial concept for a road construction SoS, that allows us to perform Lean-based optimization as well as addressing other identified concerns. Possible usage of I4.0 concepts will be pointed out, as well as differences between the construction and manufacturing domains that may require special considerations. The description focuses on the hierarchical decomposition, allocation of functionality, and knowledge representation.

A. *Hierarchical Decomposition*

As mentioned in Section II.B, construction work follows a natural decision hierarchy, with different actors being responsible for different parts. Therefore, it makes sense to also let the SoS architecture replicate this hierarchy. Typically, the whole road construction project is at the top, and at the next level, processes such as quarries, asphalt plants, or road works are represented. Within these, individual assets such as the working machines are included, as shown in Fig. 3.

The structure is inspired by existing research on autonomous vehicles, as documented in the 4D/RCS [15] reference architecture for the military domain. We have previously applied and adapted this architecture for also autonomous construction equipment [16]. 4D/RCS is hierarchical, where each higher level represents a larger geographical area and a longer time horizon with lower resolution. Although 4D/RCS is designed for autonomous vehicles, it has a great value also for analyzing manual systems since it makes explicit certain functions that must be implemented to control and coordinate movements of a number of vehicles.

Each level in the proposed concept contains a similar structure, which consists of the following parts:

- *Interface*. A common generic API is used for providing the interfaces to the level above. For this, the I4.0 asset administration shell, or a similar concept, can be used. Among other things, it can explain the capabilities of the level.
- *Constituents*. At the lowest level, the constituents are the physical assets, i.e., the working machines. These are wrapped in a similar interface. In this way, machines from different vendors can be handled. Also, manually operated machines can be included, by letting an HMI unit implement the interface, whereas an automated machine would implement the interface within its control system. The HMI unit can also, through its own sensors, give information such as position and speed of the machine.
- *Communication*. For communication within a level, a publish-subscribe model is primarily used, although peer-to-peer is also possible, e.g., in situations where cellular connectivity is poor but local machine-to-machine communication works. The publish-subscribe model can be thought of as a data bus or information broker, where different assets may be flexibly added or removed as the production evolves. It also provides buffering, that can deal with poor communication

reliability. Through established standards like OPC UA, basic security mechanisms are available.

- *World model (WM).* This is a data set that contains the up-to-date information needed for the planning and execution of operations within the layer. It is an aggregation of information coming from the layers above and below, at a suitable granularity for the needs of this layer.
- *Planning and control.* Using the world model, as well as directives from the level above and information about the capabilities of the constituents, there is functionality for planning what actions the constituents should take, and for re-planning if feedback shows that the plans cannot be followed. An important aspect in analyzing and reducing wastes prior to reaching a steady state is to simulate production based on the world model.

B. Allocation of Functionality

The hierarchical decomposition gives considerable freedom in where different functionality is allocated. Certainly, some asset-related functions need to be on-board the machines, related to capturing real-time data and executing commands. Otherwise, on-board, off-board on specific servers, and cloud solutions may be used. This includes the information describing the capability of a particular asset, which normally relates to a vehicle type and hence can be stored centrally for all instances of it. The interface to a machine can also be in an off-board solution, should the machine manufacturer choose to have only a private communication link between its machines and its own IT systems, rather than opening for direct communication with the machines. To provide a flexible allocation, container technologies like Docker [17] may be an option to encapsulate each part in the hierarchical structure.

C. Knowledge Representation

The road construction SoS is primarily driven by information and communication, and the following information sets provide central knowledge:

- *Capabilities.* A language is needed that allows the representation of different capabilities of assets and processes.
- *Plans and objectives.* The different levels need to be able to represent plans, to reason about alternative ways of getting the job done. This also includes expressing objectives to the next level.
- *Geographical data.* Road construction is about reshaping the landscape, and many questions relate to geographical data. This includes positions, topology, earth materials, etc., and is needed also to describe plans and objectives.

D. Life Cycle Considerations

RAMI4.0 divides the life cycle into two parts, namely type and instance. In road construction, a difference is that each project is unique, whereas manufacturing typically produces many instances of a given type. The type definition would therefore here correspond to project planning and the tender process. It is very valuable to have access to data produced in previous projects for doing this planning, for all actors on all levels. There are also technical aspects involved in the life cycle, such as setting up the SoS of the work site, requiring configuration support.

V. Related Work

The overall concept of an SoS for road construction presented in this paper is, to the best of our knowledge, a unique contribution. However, several previous publications exist related to different parts of the concept.

The overall problem was analyzed in [1], which also identifies on-site execution and technology as key improvement areas which could raise productivity by 20-25%. They further indicate that improved planning, communication, and coordination using techniques such as Building Information Management (BIM) [18], analytics based on Internet of Things technologies, cloud-based control, and autonomous machines can contribute to this. The need of more data for planning is also identified as a cause of large overruns and delays [19].

The potential for waste reduction has been studied in [20], results indicating that there is a potential for reducing fuel consumption of a hauler in cyclic quarry operation by some 30% through coordination of machine movements.

The application of SoS in construction has been studied in [21], focusing on how to improve resilience in a construction project. The focus seems however to be on the planning phase, rather than the actual construction. The same goes for [22], which focuses on performance assessments at an abstract level. In [23], the application of SoS to intelligent construction is discussed, i.e. the synergetic application of IT and communication to the construction project delivery processes. Five subsystems are highlighted: the physical building; the virtual prototype; sensing systems; environmental systems; and human systems. The challenges identified include the decomposition of the constructed facility; interface design; and effective integration of technological and human subsystems. In [24], the three interacting SoS of the environment, the built facility, and the construction system are studied with respect to how BIM can help improving sustainability.

The use of I4.0 for non-manufacturing applications has been considered in [25], demonstrating a potential for just-in-time delivery and cross-company Kanban systems, which is also relevant in construction logistics.

VI. Conclusions and Future Work

In this paper, we have outlined an SoS concept for improving productivity in road construction. The concept uses Lean principles for waste reduction and applies Industry 4.0 concepts to address different architectural concerns relevant in the domain.

Based on this overall concept, we plan to refine the various aspects further, resulting in more detailed specifications that can be validated through prototype implementations. The knowledge representation is a key, where languages and ontologies for planning, capability descriptions, etc. are central. Also, various life cycle aspects of the concept require further work, such as how to configure a site, how to optimize operations in order to reduce wastes, etc.

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