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PRODUCTIVITY IMPROVEMENTS IN CONSTRUCTION SITE OPERATIONS THROUGH LEAN THINKING AND WIRELESS REAL-TIME CONTROL

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Abstract

The purpose of a quarry is to extract rock material to deliver gravels, cement and asphalt to its customers. These products are important input to the construction and maintenance of road infrastructure, buildings and more. The operation of quarry and road work sites is similar to factory production, since it contains sequential production processes, tasks and activities to produce the output product. Compared to the factory, the quarry and road work processes are generally not synchronized and controlled towards the overall throughput in real-time. Some sites control parts of the production but do generally not utilize real-time technologies for the whole site and all its activities. This fact indicates a general improvement potential in increased productivity, but also unsolved challenges for the same reason.

This thesis investigate how Lean thinking utilizing real-time control and wireless communication can be used to improve productivity and safety in the operation of quarry and road construction. The main overall contribution is the identified operational improvements, its use cases, the system design constraints and challenges as well as assessed impact in productivity, energy efficiency and safety if introducing wireless real-time control to the site operation.

The results include the presentation and demonstration of a developed method based on Lean value stream mapping, for identifying wastes in sequential processes and activities including mobile machines. Further it investigates the performance and evaluates how the latest developments of wireless communication and vehicular ad-hoc networks (VANET) can be utilized within the quarry and road construction operation. The main system requirements and constraints are identified and the tradeoffs and gains in terms of system design, communication coverage, energy consumption and safety for the identified use cases are presented.

Swedish Summary – Svensk Sammanfattning

Bergtäckter uppfyller viktiga funktioner eftersom de producerar olika typer av stenkross, cement och asfaltsprodukter nödvändiga för alla typer av byggnationer såsom vägar, tunnlar, broar och byggnader och dess underhåll. Bergtäckt och vägarbetsprocessen består likt en industriell produktionsanläggning av sekventiella aktiviteter för att producera slutprodukten. Men i motsats till moderna produktionsanläggningar så är inte alla aktiviteter och maskiner styrda mot genomflödet för anläggningen, vilket gör att aktiviteter med överkapacitet genererar kostnader i form av lager och onödig resursåtgång. Detta faktum indikerar en potential i produktivitetsförbättring för dessa segment, men också olösta utmaningar.

Den här uppsatsen utreder hur den inom produktionsteknik välkända Lean filosofin tillsammans med den senaste utvecklingen av trådlösa styrsystem kan användas för att förbättra produktivitet och säkerhet för bergtäckts och vägarbetssegmentet. Det huvudsakliga bidraget är identifierade förbättringar av produktivitet och säkerhet i den operativa verksamheten, dess användarfall, systemdesignens komponenter, utmaningar och begränsningar vid introduktion av trådlösa styrsystem.

Resultatet inkluderar redogörelsen av en utvecklad och demonstrerad metodik baserad på Lean - värdeflödesanalys för att identifiera slöseri i operativ verksamhet inkluderande mobila maskiner och fordon. Dessutom undersöker och utvärderar uppsatsen prestandan och användbarhet av den senaste utvecklingen av trådlösa kommunikationssystem baserat på ad-hoc nätverk för vägfordon. De övergripande systemkraven identifieras och nödvändiga avvägningar diskuteras i form av systemdesign, kommunikationsprestanda, kostnad, energibesparingar och säkerhetsförbättringar för segmenten.

Acknowledgment

First of all I would like to start by thanking my supervisor Prof. Jakob Axelsson and advisor Dr. Peter Wallin for giving me the opportunity of this study and for their continuous support, encouragements and guidance. A special gratitude to the Volvo colleagues and mentors, especially Dr. Rikard Mäki, Peter Eriksson, Dr. Jonas Larsson and Hossein Zakizadeh that throughout the work continuously have supported and encouraged me.

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List of Papers

This thesis is based on the following published papers, which are referred to in the text by their Roman numerals.

I Rylander, D., Axelsson, J. (2012) Using Wireless Communication to Improve Road Safety and Quality of Service at Road Construction Work Sites (Poster*). IEEE Vehicular Networking Conference 2012 (VNC), Seoul, South Korea, (p.152 – 156).*

II Rylander, D., Axelsson, J. (2013) Lean Method to Identify Improvements for Operation Control at Quarry Sites. *International Symposium for Automation and Robotics in Construction 2013 (ISARC), Montreal, Canada.*

III Vernersson, S., Kalpaxidou, E., Rylander, D. (2013) Evaluation of Wireless Short-Range Communication Performance in a Quarry Environment. *IEEE International Conference on Connected Vehicles 2013, Las Vegas, USA, (p.308 – 313).*

IV Rylander, D., Axelsson, J., Wallin, P. (2014) Energy Savings by Wireless Control of Speed, Scheduling and Travel Times for Hauling Operation. *IEEE Intelligent Vehicles Symposium 2014, Detroit, USA, (p.1115 – 1120).*

Contents

I

Thesis

1. Introduction

The construction industry is a large and competitive business. In Europe alone, there are over 24 000 quarries with an annual demand of 3 billion tons translating into a 20 billion Euro turnover [1] – delivering aggregates, sand, asphalt and cement to different customers such as road construction sites. As much as 35% of the produced material from quarries are used by road and road infrastructure construction [1].

A quarry business can be described defining six main processes: (*i*) site establishment, (*ii*) exploitation, (*iii*) processing, (*iv*) distribution, (*v*) maintenance and (*vi*) reclamation [2]. Of these, the main sequential processes in operation producing the output product are *exploitation*, *processing* and *distribution*, see Figure 1. The steps of *exploitation* and *processing* address the initial phases of stone handling such as blasting or digging, and material transport to crusher and crushing activities. Since the transport is performed by machines there is an important step in the process to drive the machines back to loading area, even though the machines then are empty. When the stones have been crushed into different sized gravels the distribution process takes over. The main sub processes within *distribution* are *sorting*, *stockpiling* and *loading customers*. Between these processes there are transports to manage the stocks and customer loading.

Other required support processes to run the business include the *maintenance* which is done mainly to obtain efficient operation. Initial *site establishment* processes can be considered as the phase to prepare the site and business and are not consistently performed. Finally there are *reclamation* processes, which are performed to reinstate the area in a proper way when it has been fully utilized.

One of the main customers of the quarry is road works. Road work includes the processes for construction of new roads, parking lots, bridges and tunnels and its maintenance. The processes include the mass excavation, drainage/enforcements, road base creation and pavement as well as asphalt/concrete compaction processes.

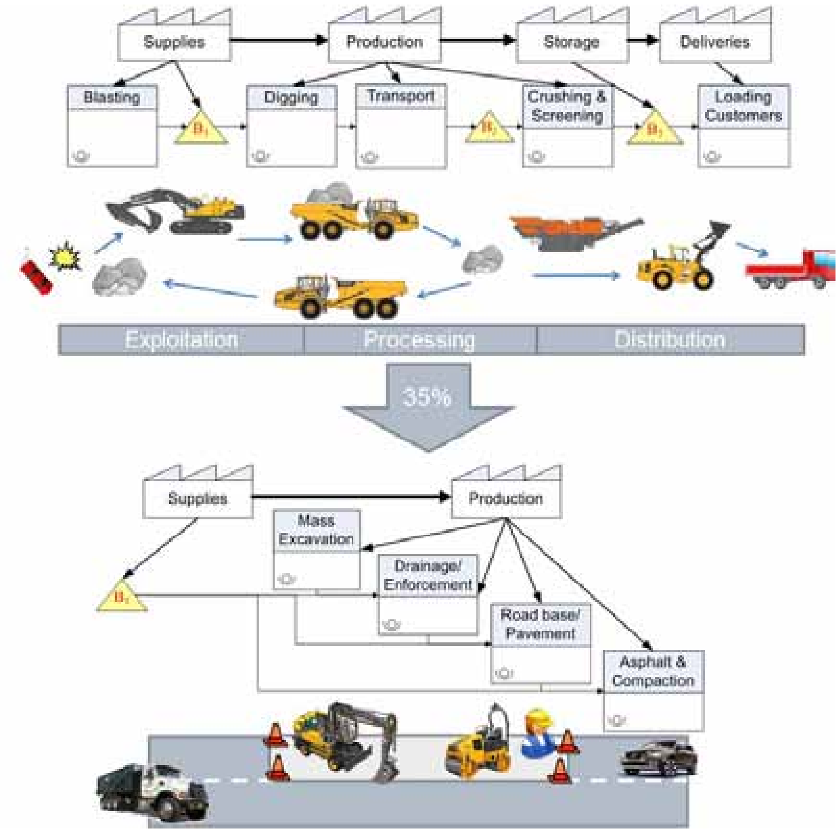

Figure 1.Main activities for quarry to road construction operation.

As identified, construction work such as quarries and road construction contains sequential activities to process and deliver the output product, similar to manufacturing plants. Due to this, the approach of this thesis is to utilize manufacturing principles such as Lean to optimize operation using real-time control technologies in a reliable and cost efficient way.

1.1. Lean Thinking

Lean can be described as a method and approach for continuous improvements of a production process. Some of the main objectives in the production are to increase quality, provide just in time delivery, and decrease production costs. A typical approach to Lean is to analyze improvements in a specific process to achieve a certain output metric. Lean defines a set of principles, tools and methods defined to assist with this work [3]. The ones that are of special interest in this thesis are identifying wastes in the production process through value stream mappings (VSM) and time studies. Those are mainly based on studying the actual real process and being present at the actual site, instead of studying the ideal, wanted or planned process. Value stream mapping is a Lean method to analyze the flow of material and information thought the production process. It is based on creating a current state value map that can be further analyzed to improve the production process. To create a value stream the different process steps and information flows within the production are identified and analyzed. To be able to analyze the value stream, each step and activity need to be measured from activity time, cycle times, setup time, value adding times, lead times and delays. The value stream is then assessed by identifying wastes and improving the current state by defining future improved state value flow.

The Lean production principles to minimizing waste in the work processes is very important. This approach is especially applicable when analyzing a value stream. Wastes are identified by actions and tasks that consume resources but do not add value to the product.

The seven original wastes can be summarized as [4]:

1. Overproduction (producing more than is needed)
2. Waiting (idling processes, waiting for work)
3. Transportation (carrying material longer distances than required)
4. Processing (the process has more steps than is really required)
5. Inventory (long lead times, too much stocks and buffers between steps)
6. Movements (unnecessary movements, changing of tools and/or patterns)
7. Defects (unnecessary amount of rework of actions and/or products)

Takt-based production is often used when the production is repetitive in cycles [4]. In Lean, takt time is defined as the pace at which a product needs to be completed in order to meet customer demand. The cycle pace and the production rate is therefore continuously optimized towards a customer demand which ideally can be considered static over a certain time. The takt time can be calculated as available working time divided by the total units demanded by customer over this time. If a process has an available working time of 10 hours and a demand of 20 units, the takt time should be 0.5 hours/unit produced. If there are repetitive cycles in the process to produce this unit the pace of these cycles are easily calculated. Say that each unit is produced by a process through 5 cycles, then each cycle should take 0.1 hours. When a cyclic process is identified a takt based approach is a good start to optimize production flow. If the process is dynamic the takt time can be dynamic as well, defining different takt times depending on the market demand over the same period of time. But this approach naturally requires a well-established control system over the production covering all sub-processes.

1.2. The Wireless Link

To implement Lean principles and balance the resources in a changing environment such as construction sites requires real-time knowledge about the activities within. However, the sites are often situated in remote areas without cellular communication coverage and the environment is harsh due to dust and solid materials that present non-line-of-sight (NLOS) issues to the wireless communication. In addition the environment and topology change over time which causes a lack of reliable map, location, path and route data. Without reliable communication the knowledge about the situation varies between different processes, activities and units/machines/vehicles leading to inaccurate and even false decisions. To be able to optimize production an accurate and reliable situation overview is therefore required at all times. Since inaccuracies will lead to inaccurate optimization, it will affect costs and productivity negatively. A reliable and predictable wireless link is therefore of utmost importance.

For wireless communication between vehicles on ground surface the available strategies can be divided into three main technology areas: satellite, cellular and dedicated short range communication (DSRC). Satellite is a good strategy to use for coverage and one subscription contract can generally be used for a wide area. The main challenges for usage of satellite communication for real-time control are the limited bandwidth and relatively high latencies as well as system costs. For cellular communication the bandwidth is rather high, but the coverage may not be guaranteed in remote obstructed areas at all time. In addition the cellular communication as well as satellite communication is based on subscriptions. Cellular and satellite communication frequency usages is based on licenses and may not be used without an agreement with the local owner of frequency licenses, often referred to as cellular network operators. Both satellite and cellular communication is also based on centralized control in which two units that want to communicate are required to pass through a base station or satellite independently of how close they are to each other causing e.g., the latency and coverage to be rather unpredictable.

In recent years there has been an attention on research activities for information and communication technology (ICT) based solutions in different road vehicle domains. Within this work there is an area of wireless communication called Vehicular Ad Hoc Networks (VANET) [5], which has a promising potential to address the needs from construction business. The aim for using VANET for road vehicles is to create an electronic digital awareness about the vehicle's surroundings. The main technical concept is that all vehicles periodically broadcast a set of attributes (e.g., speed, position, direction) to all other vehicles within range. This information is used by the receiver to increase its awareness of each surrounding vehicle's status, information and predicted future situation. This awareness within each vehicle can then be used, e.g., to optimize traffic flow, decrease fuel consumption and prevent accidents.

For local communication, referred to as DSRC, communication can be facilitated without a frequency license. However, the frequency regulation needs to be fulfilled for the selected frequency band. There is for example ISM (Industrial, Scientific and Medical) frequency bands available worldwide [6]. Usually, frequency bands vary depending on continent, but also between countries. In Europe, there are several license-free bands available for wireless short-range communication such as 868 MHz, 2.4 GHz and recently for Intelligent Transport Systems (ITS) and road vehicle applications at 5.9 GHz [6]. A number of standardized protocols are available at the three frequencies including the ubiquitous IEEE 802.11 (a.k.a. WiFi) [7]. These three bands are of course subject to regulation to minimize interference to adjacent frequency bands (e.g., the output power is limited). But also within the frequency bands, there are requirements on for example duty cycles (channel usage by individual nodes is restricted) to facilitate a large number of nodes on one frequency channel. The three mentioned frequency bands have different physical characteristics due to the carrier frequencies which affects the performance. Lower carrier frequencies have the possibility to penetrate buildings (e.g., 868 MHz) whereas signals at 5.9GHz are subject to much multipath (the signal bounces off its environment and several replicas of the same signal reaches the receiver).

1.3. Systems Engineering

To establish the Lean thinking for productivity improvement of construction operations utilizing wireless control systems, a system approach is needed.

The systems engineering discipline follows a holistic way of thinking where ideally the full lifecycle of a system is addressed already in the concept design phase [8]. In this case that requires both functional and non-functional requirements to be fulfilled. Functional requirements solve a specific problem or need addressing functional use cases. But the non-functional are as important. Non-functional requirements describe the need for a system to comply with, e.g., costs, performance, usability and maintainability. Costs are then not only costs for purchasing, but also installation, configuration, maintenance and disposal.

Within systems engineering there are descriptions of methods for how to develop a system according to the system engineering principles. One such method is the systems engineering development process, referred to as the V-model or Vee-model, see Figure 2. Following the Vee-model in the concept and development phase [9], identifying the user needs and requirements are the first phases followed by the architecture and system design. Each of the phases in the downstream development cycle has a corresponding phase in the upstream testing cycle.

This method is relevant to use in this thesis due to that the area is rather unexplored and the use cases have not been fully identified. Therefore this thesis focuses on the initial phases of the process to identify the use cases, concepts of operation, user needs and the development of system requirements, limitations and approaches for the target system.

To address the theory that construction operation productivity improvements can be done with Lean thinking, user needs as operational wastes, use cases and system requirements need to be identified and described. Since there are

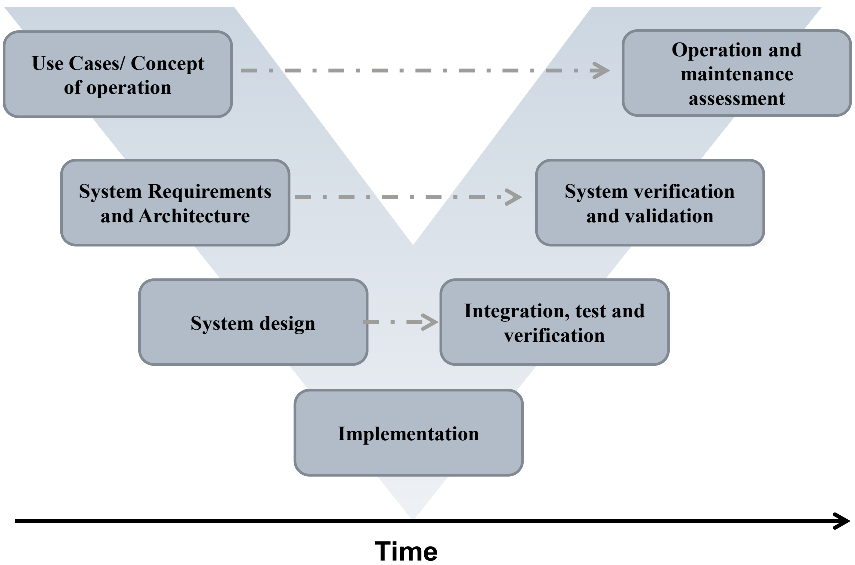

Figure 2. Vee-model principle.

physical constraints in real world operation the system design needs to incorporate the available technologies and assess them thoroughly. While considering the life cycle of a system solution for a market, the solution would benefit from being interoperable in several segments and incorporate as much benefits for the users as possible to minimize the return of investment of the product. This thesis proposes possible solutions to the above described problem.

1.4. Thesis Outline

This Licentiate thesis is presented as a collection of four published papers. The remainder of the thesis is structured as follows; In Chapter 2 we present the motivation to the work, scope, research questions and research method used. In Chapter 3 we present the contribution and summarize the four papers that are included and how they are relevant for the thesis. In Chapter 4, we discuss and present the results, and in the final chapter, the conclusions and future work is summarized. Finally, in part II of the thesis the included papers are presented.

2. Research Scope

In this chapter the motivation of the research is explained. The motivation and its challenges are used to form concrete research questions and derive hypothesis. Further the overall research methodology used to address the questions is explained in this chapter.

2.1. Motivation and Positioning of the Work

The scope of this thesis is the road construction and quarry and aggregate segments. The main three reasons for including the two segments are that:

- These segments are connected in the production chain since the quarry and aggregate sites produce the material used in road construction work, see Section 1, Figure 1.
- The machines and equipment used, such as excavators, wheel loaders and haulers can be present in both work sites. Therefore a supplier and owner of machines and equipment benefit if the technologies and applications are interoperable and compliant towards both segments need and processes.
- The quarry and aggregate and road construction segment are comparable since they work in a sequential process to deliver the output product. Each process step is dependent on the deliveries of the preceding step for efficient operation.

In modern Lean approaches, wastes such as inventories, over capacities, buffers, downtime and waiting are costs that should be reduced without decreased production performance and quality. Inventories, over capacities, buffers and waiting are mainly results of lack in resource utilization or production planning and control. The sequential process layout similar to production factories therefore indicate that there would be a production improvement with the potential of reducing wastes within the identified scope while controlling the production.

Unwanted production downtime can be related to machine maintenance and machine failure breakdowns but also due to accidents resulting in a lack of work people and available equipment. The accident risk for road works has been presented by available statistics concluding that “for freeways in USA, road works increase the accident rate with 21.4% [10]. In addition, 41% of all accidents in quarries are vehicle related [11]. The authors in [11] describe common accidents such as “run over by a vehicle” and “vehicles colliding with plant or other vehicles”. These facts indicate a potential in accident avoidance using VANET based warning systems similar to the developments for road vehicles. Further the technology implies a cost efficient productivity potential if introducing a system that prevents accidents and simultaneously increase productivity while controlling the production.

Since the operative production in these segments mainly are performed by mobile machines the communication needs to be wireless. Further since the purpose of the work performed is to blast, transform and process rock and sand material, infrastructure such as cables for wired communication and power supply is challenging to facilitate. Depending on e.g., local conditions and machine characteristics, there are differences in activities cycle time. Presenting a draft estimate, unloading can take roughly 20-40 sec and transports can roughly take between 1 to 10 minutes to perform within a site [II]. To control the production, the control loops must manage events and deviations instantly during this time and deliver scheduled directives continuously without considerable delays to be effective. In the road works case it is even more challenging since the work site geographically moves over time. In addition the sites are often remotely placed and for quarry and aggregates the normal layout is a broad hole surrounded by solid rock material working as isolators, interfering wireless communication with remote units. All together these characteristics present a challenging environment for wireless communication to facilitate effective reliable control systems.

2.2. Research Questions

The main theory of this thesis is based on that construction operations are sequential processes similar to a manufacturing plant. Within manufacturing the Lean approach is well known but it has not been fully explored within real-time control of quarries and road works. To analyze the operation using Lean there are several methods available, one such method is the values stream and waste analysis, which has not been applied to the quarry and road construction segments. Based on this fact the first research question can be derived:

Research Question 1: Can Lean manufacturing principles and methods be applied to identify real-time improvement opportunities and stakeholder needs in construction operation? (Paper II)

A Lean approach based on takt time to control the production processes in real–time to minimize waste in operation requires available and reliable communication. Wireless communication is needed since the machines at the sites are highly mobile excluding wired communication. Wireless communication is rather unexplored for the quarry and road construction segments, but related research findings from other domains may be applicable. Considering the known constraints and limitations of wireless communication in terms of performance and costs, how will it perform and what are its characteristics to the addressed segments for this thesis. Based on this insight the second research question can be formulated:

Research Question 2: How can wireless communication technologies, systems and solutions from other domains be utilized within construction work site operation control to address the connectivity issues and what is the performance? (Paper I, III and IV)

The current research findings combined with Lean value stream analysis potentially can assist with the identification of stakeholder needs and operational wastes. A systems engineering approach is suitable to understand what system solutions are feasible. A system approach does not only require that the functional requirements are met, it also requires that the nonfunctional requirements are fulfilled and that the system benefits from a life cycle perspective are assessed.. A system must then fulfill the identified needs within the cost limits of what benefit the system solution contain. The costs need to include the full life cycle including installation, maintenance, configuration, monitoring and diagnostics, management and disposal of the system to be successful. These characteristics need to be defined in the system requirements specification. To obtain these requirements an assessment of costs involved both in terms of benefits and constraints need to be available. To address this need the following research question is formulated:

Research Question 3: Based on stakeholder needs, what benefits and improvements can be addressed utilizing wireless communication at quarry and road construction work site operations and what are its constraints and challenges? (Paper I, II and IV)

2.3. Hypotheses

To address the research questions, each question has a related hypothesis that is challenged by the research performed.

1. While utilizing manufacturing principles such as Lean value stream mapping to find operational improvement potentials we can identify technical challenges and then utilize knowledge from other disciplines to design cost efficient solutions that addresses the need from the users.
2. VANET technologies developed for road vehicle accident prevention can be used as a local sensor to exchange required data between vehicles and machines at construction sites to facilitate real-time control and required information aggregation to fulfill the need from the stakeholders identified.
3. A cost efficient system of systems can be designed for the identified improvement use cases with components that are interoperable towards both the segments within the scope of the study.

2.4. Methodology

The main method used in the research is identified as "Applied inductive scientific method" [12] through iterative improvements and empirical studies. The method is considered as "applied" since we are working on real users and real systems, "Inductive" since the real world studies of adaptive individuals never can be a representation of all individuals at all time. What we do is to implement and collect a reasonable amount of data to supply strong evidence that the results at least are valid within the studied scope and a logical reasoning about the conclusions can be made.

The main work flow:

- Create theory: Theory is formulated and research questions derived from the theory.
- Derive hypothesis: To address each research question a hypothesis was formulated.
- Formulate theoretical analysis/experiment to test hypothesis: Different analysis/experiment strategies was formulated to test each hypothesis.
- Collect empirical data on application domain: For each hypothesis and segment within scope the required data was collected. The data has been collected using different methods based on the data characteristics. In some cases data was already available, such as accident risks and its characteristics but most data was not available. Data has mainly been

collected through field measurements and the data types, method and tools vary depending on the characteristics of the data type and user operation. The main data types collected were time costs in operational wastes, fuel costs based on machine driving characteristics and data packet reception ratio for wireless communication,

- Perform theoretical analysis (test hypothesis): During the analysis phase the data collected from research findings and experimental results was aggregated and visualized in various forms to analyze the data and test the hypothesis.
- Evaluate results to obtain positive/negative evidence. The data collected was then evaluated and conclusions addressing the hypothesis based on data characteristics and method used to obtain it was done.
- If contradiction or unsatisfying: Theory was modified and iterated. Following the method, unsatisfying results imply a need to modify the theory and an iteration of the method.

In practice the thesis has based the design on empirical field studies of actual use of machines and operation of construction sites. The method for identifying improvement potential and benefits is based on Lean production and real world analysis. The need and system requirements have initially been identified through real world data collection simultaneously as the current literature and findings within the field have been analyzed. The identified needs have been assessed through information and value flow identifications and described in value streams. Based on the needs described, system constraints have been identified, assessed and evaluated using both further empirical inductive studies and logical reasoning.

The method used for approaching the research questions can also be referenced to as an agile method of systems engineering. This since the approach of system requirements, design, implementation and verification are iteratively approached and continuously improved. Anyhow the basic applied inductive method has been used for each of the included papers, but with slightly different theories and use of empirical data to address the different research questions and segments in a good way, which is further explained in each of the papers.

2.5. Related Work

Production real-time control utilizing wireless communication within construction is a relatively unexplored area. Major vehicle manufacturers such as Volvo have products utilizing wireless communication mainly based on cellular communication for maintenance and productivity monitoring. Very few solutions on the market utilize low latency short-range communication for active safety applications and real-time productivity control in construction. Since the research in this topic is immature the related topics of Lean construction, construction control and active prediction and wireless real-time control in other domains are closest related and their relation explained further below.

2.5.1. Lean Construction

Within the construction area, a research field called Lean construction has been established. Within this field Lean principles has been analyzed and evaluated for the utilization in the construction domain [13]. Even though Lean construction has the potential of improving productivity in all types of construction, the research has mainly been on operation management and the construction segments of fixed installations and the normal final product, e.g., structures, buildings and roads referred to as site-position assembly [14]. Not very much research can be found utilizing Lean construction on the quarry and aggregate site for operation control.

Using the current state of the art, the site and production can be planned and configured with the machines' capacity and performance as well as designed in layout and placement for optimally calculated throughput with regards to the uncertainties in the input data [15].Uncertainties can be processing time, lead time, fluctuations in production capacity and deviations in customer demand. Accordingly decision makers can manage a production plan based on tradeoffs of total cost and acceptable fulfillment of market demands.

The lack in current research is the real-time management of operational deviations from the planned production configuration. When production rate of the crusher is decreased, the capacity of the other machines is usually static. While several machines can be used for loading and transports, these are not synchronized in real-time towards each other or the throughput of the site. While throughput is the rate at which the system generates income through sales, operational expenses is how much the production costs and inventory is the cost for buffers that are needed within the production. Therefore there is a lack of research in modeling the full site and optimizing the productivity in real-time.

2.5.2. Construction Control and Active Prediction

Within recent research on construction operation optimization, attention has mainly been on how to optimize and control isolated production activities during operation. These discrete process and machine optimizations have either focused on the mobile machines such as excavators, wheel loaders, articulated haulers and trucks or the geographically static machines such as crushers and sorting and screening processes within quarries. Mobile machines used for mass transportation and movements have been shown to have a potential in fuel savings while controlling speed and gear shifting due to topology [16]. The size reduction processes such as blasting and crushing as well as sorting and screening have shown to be possible to improve in terms of machine wear and production quality as well as energy consumption and machine utilization. The research has highlighted the importance of adapting the crusher to time dependencies and its variables such as material size as well as feeding pace [17, 18].

In addition, there have been numerous simulations presented where different approaches to controlling the driveline of mobile vehicles through terrain and trajectory predictions and intelligent gear shifting have been investigated [19]. For optimal productivity it has been derived how total cost of ownership is affected by having the right size and type of machine for a specific task and site [20]. But anyhow there is a need to handle fluctuations in the production and need of site overcapacities to manage deviations in the production chain. In addition, manufacturers supply machine and motor specific fuel characteristics data for simple driving cycles [21] but not field trials data in application usage where these data have been validated.

Another research area of construction is planning, design and information management. Here research concludes and identifies strategies and processes [22] for how information management should be handled efficiently. The utilization of wireless communication for specific tasks [23] have been investigated and the desired position and need of information described [24].

What is lacking from current research is models of the site processes and system constraints such as how real world energy consumption of applicable mobile machines are affected by driver characteristics and path characteristics such as stop-and-go driving, different speed profiles, road topologies and consequently changes in travel times in quarry operation.

2.6. Wireless Communication and Vehicular Ad Hoc Networks (VANET)

Within the road vehicle domain the recent research for wireless communication has mainly been focused on developing VANET technologies and related applications. Within this field a lot of focus has been on the ITS station [25] e.g., communication architecture and its related functions and mechanisms [26], performance [27] and vehicle centric applications for road traffic environments. The applications include e.g., electronic brake light warning, green light optimal speed advisory and emergency vehicle warning but also road works warning applications.

The related road works applications based on VANET have been developed mainly from a road user perspective. The applications include road works information as a warning or trigger for actions. This concept has been developed and demonstrated within multiple projects such as EU-CVIS [28], EU-SafeSpot [29] and EU-CO-Cities [30] and recently described as "warnings about hazards in a work zone" and "warnings about upcoming work zone" in a suggested revision to SAE J2735 referred to as J3067 [31]. The result from these efforts includes specifications of the use cases, information protocols and its architecture for data exchange between ITS stations such as vehicles and road work sites. This has also been developed, considered and included within wireless message standardization in ETSI-ITS [32], and in ISO-TPEG [33].

It has been identified that a system solution needs to be technically, economically and operationally feasible [22] which implies that a solution needs to be interoperable and widely used for it to be useful. But this research has not been covering how the emerging VANET technologies and standardized protocols can be utilized within the construction operation or how to ensure reliability and accuracy of the data provisioned. There is a lack in related research and standardization activities on how the actual layout and wireless functions at the road construction work site should be designed, utilized and technically solved in an optimal way, considering functionality, interoperability and quality of service. In addition there is a gap of knowledge about the performance of wireless short-range communication standards within closed construction site activities such as quarries.

3. Main Contribution and Included Papers

The main contribution to science and industry is the operational improvement method developed and the assessment performed. This include collected system requirements for improving construction productivity and safety through real-time control and information sharing based on Lean principles and available wireless communication technologies. The contribution is based on real world empirical field studies of operational wastes and quantification of benefits as well as application design requirements and implementation considerations. The presented results indicate important aspects of operational improvements and highlight several areas of need for future research.

3.1. System architecture

To further define the context of the contribution an overall system architecture description is provided. The overall system architecture approach developed and used in this thesis is a mix of centralized and distributed intelligence where there need to be a coordinating function to manage the system, dispatch instruction and missions and monitor the system, see Figure 3. Besides the overall instructions needed from the coordinator, the vehicle itself controls and optimizes the movement and related actuators. The main data transfer strategy between vehicles for real-time optimization and crash

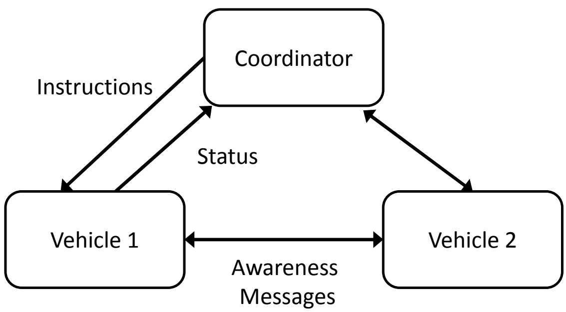

Figure 3. Holistic system architecture

avoidance is performed through VANET. The main arguments for this decentralized intelligence and VANET approach is the system independency of continuous reliable wireless communication. But since the decisions are made locally shorter latencies and increased functional safety due to the decreased system component dependencies are obtained. Further benefits are the usage of license free ISM bands for communication which does not require procurement and subscriptions to local operators.

From a vehicle and mobile machine perspective the functional architecture and its main components approach used are shown in Figure 4. The main components are the machine control and driver feedback functions. These functions need instructions from an application which require facilities to collect information and base its decision and recommendations on. The application modules identified to recommend on a certain movement can be described as the optimal way and the safe way. The safe way is managed by the crash avoidance system which continuously advices on safe movements to prevent crashes. The optimal way is managed through a scheduling system which continuously advice on an optimized movement towards the throughput and activities on the site. It is likely that there are situations from which the safe way and optimal way deviate, for which reason an overall vehicle control logic is required to finally decide on the usage of machine actuators and driver feedback/HMI. For the two different logical applications to be effective and able to recommend on one certain movement given a specific situation, they require a model and sensing platform. The functionality of the main identified facility capabilities required can be described as:

- *Machine Model:* Describes the machine's capability and energy consumption and are continuously updated based on load, wear and environment (weather and traction).
- *Path Model:* The module describes the routes, distances and topologies of the area.
- *Mission Manager:* Describe the destinations, purpose and objective of the activity and movements that are required.
- *Ego Positioning and Movement System:* The module describes the position and movements such as the velocity of the machine.
- *External Sensing and Perception System*: Describe the position, destination and movements of other vehicles and units in the surrounding environment.

Towards this holistic and in-vehicle architecture the four papers address different important aspects described further below.

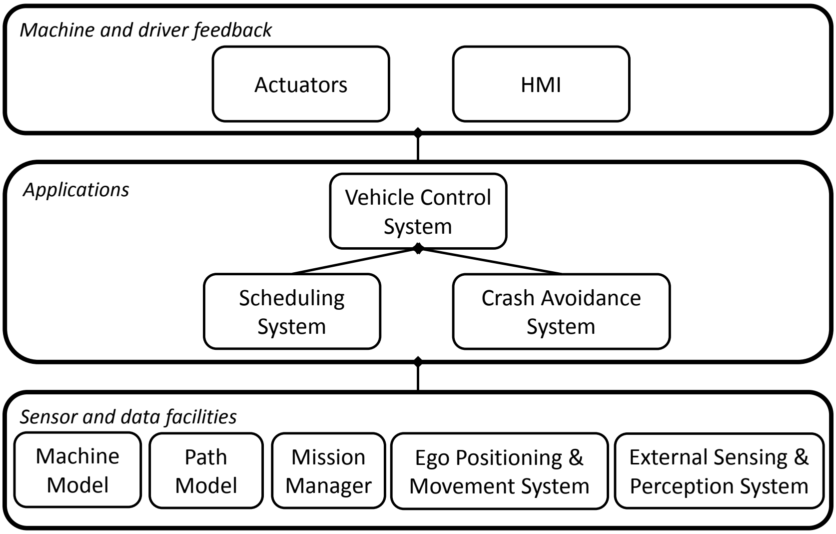

Figure 4. Main functional components of the vehicle system architecture.

3.2. Paper I

In recent years there has been an increased attention for using VANET to improve safety, efficiency and facilitate automation functionalities for road vehicles. The aim for using VANET for road vehicles is to create a reliable electronic digital awareness about the vehicle's surroundings. The main technical concept is that all vehicles periodically broadcast a set of attributes (e.g., speed, position, direction) to all other connected vehicles within range. This information is used by the receiver to increase its awareness of each surrounding vehicle's status, information and predicted future situation. This awareness within each vehicle can then be used e.g., to optimize traffic flow, decrease fuel consumption and prevent accidents.

This paper's contribution is the investigation of how wireless communication and vehicular ad hoc network (VANET) based technologies can be applied in relation to road construction work sites to improve safety and increase efficiency and sustainability. It present a set of use cases, its challenges and discusses how to design the flow of data for a number of functions and how to operate the functions at the work site even at low VANET penetration rates.

The method used can be described as constructive research following the main method of thesis. The research presented based on challenges from state of the art in VANET application developments, which were assessed based on empirical data available as accident characteristics from publicly available statistics. This main source of information was complemented by interviews for improved operational descriptions and user needs. The results are objectively argued and presented with logical reasoning.

While implementing VANET technologies, the applications described identify the potential in increased productivity at a road construction site and how increased visibility of site activities impacts traffic and improved road safety. The basic consolidated architecture is shown in Figure 5. The paper also highlights important implementation considerations and the need of availability and utilization of open standards for this purpose.

My contribution: I am the main author of the paper, and I initiated the need for the study, designed the data collection, performed the data collection and made the analysis of the data presented.

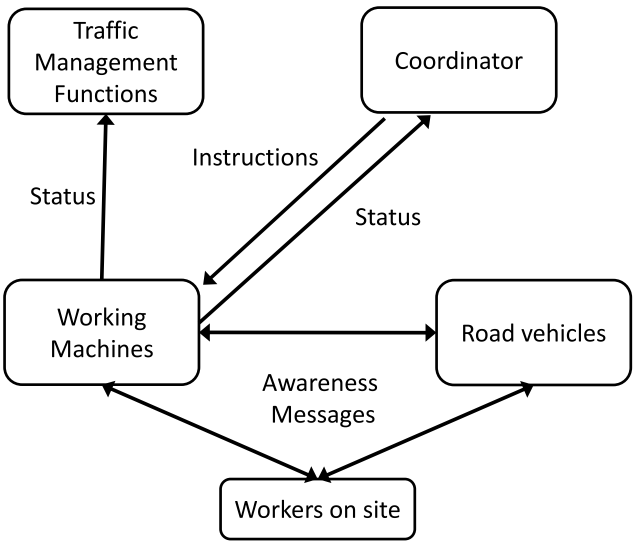

Figure 5. Road construction communication architecture.

3.3. Paper II

The operation of Quarry and Aggregate sites are similar to factory production, since it contains sequential production processes, tasks and activities to produce the output product. Compared to the plant though, the quarry processes are generally not synchronized and controlled towards the overall throughput of the site in real-time. Some quarries control parts of the production but do generally not utilize real-time technologies for the whole site and all its activities. This fact indicates a general improvement potential in increased productivity at quarry sites, but also unsolved challenges for the same reason.

The theory to optimize the construction site towards its throughput in real-time is based on well-known production principles. A potential improvement application should therefore be based on knowledge of the overall production system. Each activity should be synchronized towards each other, the throughput and the identified bottle neck. This way productivity is optimized towards customer demand and sales simultaneously as inventories, buffers and production costs are minimized.

For this purpose the main contribution of this paper is the presentation of a Lean based method for how to describe the quarry processes to identify improvement potential within a work site. The method developed and demonstrated within the paper is to utilize waste identification principles based on VSMs, see Figure 6, from which data is obtained by time studies. The method presented includes four sequential steps, see Figure 7. The first step is to initially observe the site operation to identify the main processes and to create the VSM legend for the site. Based on the VSM legend, time studies can

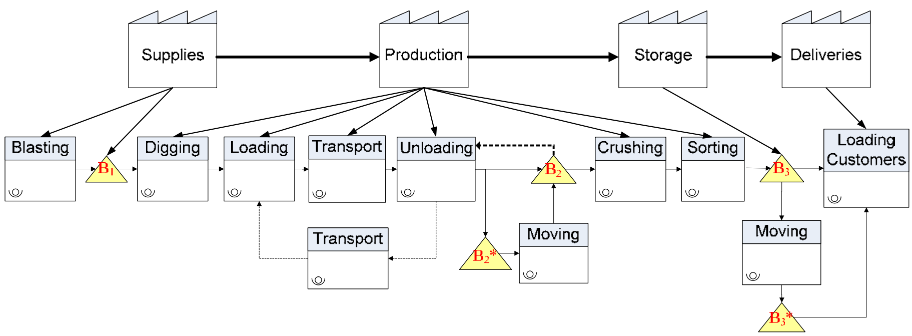

Figure 6. Quarry Value Stream Legend.

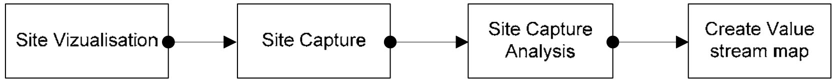

Figure 7. Site Capture Method.

be performed to collect the cost in time for each activity. In the presented data, continuous simultaneous recordings were done using video cameras to be able to capture all activities. The analysis based on time measures from the video captures supply the needed data for each activity to be able to fill in the VSM for the specific site operation. When the VSM is finalized the analysis of the operation can be performed.

During this method demonstration of real world quary analysis, the main improvement potential was found in the areas of transports and buffer/inventory handling as well as in the customer delivery/loading activity. There was an overcapacity in the transporting activity, which purpose is to feedthe crusher. An average waiting time of 33% of the cycle time was observed. In addition non value adding stops in relation to productivity occurred due to transport vehicle meetings in narrow road segments. During a site data collection non-value adding stops occurred at 2 out of 11 transports observed.

The method has proven to be a good way of identifying wastes and an improvement potential for control and scheduling technologies at quarry sites. What is important to highlight is that the method is a single window analysis and does not statistically present the real measures for the sites productivity. In addition the identified productivity improvements based on increased control and automation indicate challenges and needs in wireless communication and sensing technologies.

My contribution: I am the main author of the paper, and I initiated the need for the study, designed the data collection, performed the data collection and made the analysis of the data presented.

3.4. Paper III

For geographically remote construction sites such as quarries there is a need of dedicated short range communication to be able to create reliable vehicular ad hoc networks (VANET) to facilitate crash avoidance and control machine and fleet movements. The road work topology is comparable to the general road infrastructure. For road vehicles in general road infrastructure topologies there are research results and communication behavior analysis available, but for quarries it is very limited known knowledge presented. The quarry environment is a harsh environment due to all the solid material, rough topology and dusty environment.

This paper's contribution is a real world evaluation of open license free communication within the ISM bands available for such communication at 868MHz, 2,4GHz and 5,9GHz. The results presented show important communication possibilities and challenges for communication coverage, latencies and data throughput considering system design of real-time site control applications.

The method used was to equip two vehicles with the technologies and define a suitable protocol to send direct packets and log the packet reception ratio in a set of test cases. The test cases where defined as ideal Line of Sight (LOS) characteristic and non-line-of-sight (NLOS) within quarry environment and NLOS in the surrounding quarry area.

The results show how the different wireless technologies behave using the maximum allowed output power, communicating relevant data packages at a frequent manner. The results indicate relevant differences between the technologies depending on environmental characteristics. The results also present longer ranges than expected in LOS environments, where most technologies could facilitate coverage with a radius of more than 1500 m in beneficial conditions. Test in obstructed situations showed significant differences between the frequency bands where one could communicate and others did not provide coverage even within a few meters. Anyhow, the frequency band planned for VANET at 5,9GHz was recommended for the segment based on its combined capability of bandwidth and range, even though the coverage limitations in obstructed situations was highlighted.

This knowledge is crucial for developing crash avoidance and vehicle mission scheduling optimization applications for the target segments. This is since behavior and inaccuracies in the data used for the applications can be predicted based on knowledge about topology, road segments used and location and amount of vehicles within vicinity

My contribution: I initiated the study and defined the main scientific method, scope and target for which I recruited and supervised two master thesis workers and co-authors to design, implement and perform the data collection which made the basis for the paper.

3.5. Paper IV

Assuming a wireless based control system that would control the speed and throughput of the different processes and activities addressing the needs identified in Paper II, there would be a fuel reduction potential in controlling the mobile machines. For this purpose there is a need for detailed machine models of machine fuel consumptions for different application characteristics and velocities. The main scientific contribution of this paper is the presentation of fuel measurements based on different velocities, site application characteristics and travel times for an application relevant machine. The fuel measures accounted for reveals important aspects regarding how velocities and driver characteristics impact fuel consumption. In addition the applications and challenges in controlling the machines are discussed.

The characteristics that where included address the costs for non-value adding stops during production by measuring the increase in fuel consumption by adding stops per kilometer and with different travel times/average speeds. In addition the measurements include characteristics for driving fully loaded or unloaded at different speeds and how rough topology affect the fuel consumption at different travel times.

It was determined that the amount of stops per km added approximately 10% fuel consumption per stop. The change from driving with the highest gear and speed to optimal gear and speed increased travel time with 37% which resulted in decreased average fuel consumption per lap of almost 25%. Concluding the results of fuel measurements, it highlight a potential in fuel savings of up to 42% and a typical improvement of 20-30% depending on machine speeds, stops, application and site characteristics for the same activity performed.

My contribution: I am the main author of the paper, and I initiated the need for the study, designed the data collection, performed the data collection and made the analysis of the data presented.

4. Results

A summary of the results can be described in relation to the research questions formulated:

Research Question 1: Can Lean manufacturing principles and methods be applied to identify real-time improvement opportunities and stakeholder needs in construction operation?

Paper II show how Lean principles and methods can be used to identify stakeholder needs and real-time improvement opportunities. This was done presenting a method for how to use VSM analysis identifying operational wastes while collecting and using data from real world operation. The method proved to be successful and identified and quantified several user needs for which real-time control is required as a system solution. The results from this paper shows that Hypothesis 1 is true except for that the cost efficiency of the solutions need to be further verified.

Research Question 2: How can wireless communication technologies, systems and solutions from other domains be utilized within construction work site operation control to address the connectivity issues and what is the performance?

In Paper I and III we show how wireless communication technologies developed for road vehicles such as VANET technologies can be used to facilitate communication within the construction site. We present several use cases and discuss the similarities and present the different challenges and constraints that need to be included in the system solution. Further we assess the performance of VANET using available ISM bands in challenging the application domain. The presented results from these papers show that Hypothesis 2 is true.

Research Question 3: Based on stakeholder needs, what benefits and improvements can be addressed utilizing wireless communication at quarry and road construction work site operations and what are its constraints and challenges?

In Paper I we contribute with stakeholder needs analysis based on known statistics such as accident statistics and on state of the art within VANET research related to road works. The paper presents a set of use cases, its challenges and discusses how to improve the operation and design the flow of data for a number of functions and its operation.

In Paper II we further contribute with identified use cases based on empirical data observed and collected by studying the quarry operation. The operational improvements and waste identified were assessed, presented and discussed.

In Paper IV we further explore what the identified wastes from Paper II cost in energy consumption and we present the relation and tradeoffs between speed, travel times, non-value adding stops and energy consumption. A machine model for usage within a scheduling algorithm was presented but also the challenges and the presented constraints and limitations.

Concluding the results from the three papers I, II and IV, shows that we have addressed Hypothesis 3 making progress on several important components but that more assessment is required to be able to very that it is true.

5. Conclusions

This thesis presents the user needs, system requirements and discusses system solutions to increase productivity and safety at road construction and quarry and aggregate operation. The solutions discussed indicate that VANET technologies developed for road vehicles may be one of the main technologies to enable the improvements identified.

For road construction a system based on VANET to increase safety for workers and road traffic is presented addressing the identified operational needs. Further a system including VANET as both a sensor and information distributor has the potential of increasing efficiency and transparency of the road construction and road maintenance operation.

While deployment of VANET for road vehicles are emerging, road construction site improvements based on VANET can be among the first applications for market introduction. The applications have the potential of improving road safety and quality of service even with low penetration rate and amount of equipped road vehicles

Construction machines used in the operation are suitable objects to place wireless communication and VANET equipment on. This is the case due to its power supply, location at the site and natural height which provide good conditions for acceptable communication coverage and range, for e.g., collecting, analyzing and disseminating information required for the applications.

Specific for the quarry and aggregate segment the included papers present:

- A Lean method to identify waste in operation
- Quantitatively obtained operational waste of up to 33% of cycle time based on real life operation observations using the Lean Value stream method and time studies
- Quantitatively obtained values in fuel reduction of up to 42%depending on waste characteristics
- Quantitatively measured performance of available wireless short range communication and challenges for usage within quarry environments

- System requirements and challenges for implementing a wireless system for control of production and machines at quarry sites

5.1. Discussion and Future Work

This thesis has identified operational wastes, improvement potential and the main challenges for introducing real-time control to the identified segments. Further it has quantified the value of waste in energy and fuel consumption and identified, presented and assessed the main challenges in wireless communication and control for a sustainable system solution.

The main reasons identified for the quarry and aggregate as well as road work business to currently not utilize real-time control and scheduling algorithms for becoming more Lean in the operation is based on its characteristics:

- The sites move and change over time and the movement can be rather unpredicted. In addition the ground is processed and blasted which affect the paths and digital map data that is needed to schedule work and calculate and predict travel times.
- Construction sites lack in reliable and predictable communication infrastructure and the business size and revenues as well as site flexibility affect the possibilities for installing and maintaining fixed wifi based infrastructure. Compared to mining business which regarding the activities and somewhat the equipment used are very similar to a quarry, the underground mines does not change the paths as often and the communication infrastructure is much easier to maintain. For mining business it is considered as common to have digital maps and available communication for real-time control. Even though the positioning underground is technical different from the most common system used above ground based on satellite triangulation as GPS.

Future work will further use the achieved results and describe possible tradeoffs based on dependencies of production rate, output and costs. We will develop algorithms for site and machine mission controls using the system requirements presented and assess system architectures depending on both functional and non-functional requirements considering both decentralized and centralized business logic strategies

Further we will assess and scale the machine, driver and path models to be able to control energy consumption optimization towards task and deadlines for more machines, segments and site profiles.

A challenge which is of great importance is the communication data protocol strategy and approach to exchange different information attributes between machines at the sites. System interoperability and scalability need to be further assessed and the data reliability and communication predictability need to be further evaluated

In addition, the safety of the applications needs to be further analyzed and operational and technical feasibility of implementing crash avoidance system applications into the quarry and road construction segments must be evaluated.

Finally there is a need for more research activities within simulation and field operational tests where construction site improvements are fully considered and assessed. The assessment needs to be value stream oriented instead of discrete production process oriented and drive Lean system implementation rather than isolated process improvements in individual machines, and activities.

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