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Productivity Improvements in Construction Transport Operation through Lean Thinking and Systems of Systems

David Rylander

MÄLARDALEN UNIVERSITY
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School of Innovation, Design and Engineering

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Akademin för innovation, design och teknik

Abstract

The purpose of a quarry is to extract rock material to deliver gravel and raw material to its customers. The products can be further processed to e.g., extract minerals such as iron or to produce cement and asphalt. These products are an important input to the construction and maintenance of road infrastructure, buildings, and more. The operation of quarry and road work sites is similar to the manufacturing industry since it contains sequential processes to produce the output product. Within the operation, there are cyclic transport activities that in general are not synchronized and controlled in real-time towards the overall throughput. This fact indicates a potential to increase productivity but also points at unsolved challenges.

This thesis investigates how Lean and systems thinking combined with real-time control and optimization technologies can be used to improve productivity and safety in the transport operation within quarry and road construction. The main contributions are the identified operational improvements, its use cases, the system design constraints, operational characteristics, and models as well as assessed impact in productivity, energy efficiency, and safety.

The results include the development and demonstration of a method based on Lean value stream mapping, for identifying wastes in sequential processes and activities including mobile earthmoving machines. Operational wastes of 33% are presented from real world operations. Related fuel savings of 42% are measured in controlled environments. Further, the thesis presents and assesses a system design for transport optimization purpose. A study of how wireless communication and vehicular ad-hoc networks (VANET) can be utilized and its performance within the quarry and road construction operation is presented. The main system requirements and constraints are identified, and the trade-offs are discussed in terms of system design with a system of systems perspective. Energy consumption models are developed for optimization purposes and the key characteristics of real world operation is identified. Finally, a prototype system has been developed and tested in controlled and operative environments. In controlled trials, a fuel reduction of 20% for individual machines was obtained using the suggested optimization technique.

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Abstract

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Sammanfattning

Vid dagbrott och bergtäkter bearbetas jord, berg och stenmaterial för att leverera råmaterial till dess kunder. Slutprodukten kan vidare processas för att utvinna olika mineraler eller för att producera cement och asfaltsprodukter. Dessa produkter är nödvändiga för alla typer av byggnationer såsom vägar, tunnlar, broar och byggnader och dess underhåll. Bergtäkter och vägarbeten består likt en industriell produktionsanläggning av sekventiella aktiviteter för att producera slutresultatet. 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 avhandlingen utreder hur den inom produktionsteknik välkända Lean-filosofin tillsammans med ett systemtänk och den senaste utvecklingen av trådlösa styrsystem kan användas för att förbättra produktivitet och säkerhet för bergtäkts- och vägarbetssegmenten. Det huvudsakliga bidraget är identifierade förbättringar av produktivitet och säkerhet i den operativa verksamheten, dess användarfall, systemdesignens komponenter, modeller, utmaningar och begränsningar vid introduktion av trådlösa styrsystem.

Resultaten inkluderar redogörelsen för en utvecklad och demonstrerad metodik baserad på Lean, där värdeflödesanalys används för att identifiera slöseri i operativ verksamhet inkluderande mobila maskiner och fordon. Operativa slöserier på 33% från verklig drift identifieras. Relaterade bränslebesparingar för maskiner på 42% identifieras i kontrollerad testmiljö. Vidare presenteras och utvärderas ett systemkoncept med syftet att styra maskinparametrar mot ”just in time” för maximerad effektivitet. Användbarhet och begränsningar hos trådlösa kommunikationssystem baserade på lokala ad-hoc nätverk studeras. De övergripande systemkraven identifieras och nödvändiga avvägningar diskuteras i form av systemdesign med ett system-av-system-perspektiv. Metoder och modeller för energikonsumtion presenteras och analyseras där besparingar kvantifieras. Slutligen har ett prototypsystem utvecklats och testats i kontrollerad och verklig operativ drift. Bränslebesparing på 20% påvisas för enskilda maskiner i kontrollerad miljö vid användning av systemet.

Acknowledgment

As I am approaching the end of my journey as a doctoral student, I want to express my gratitude to the people and organizations that made it possible. It has been a very exciting, fun, educational, and inspiring journey, but occasionally also a difficult experience for which I am grateful for all the support provided.

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My deepest gratitude to my family and friends, especially my parents Leif and Kerstin, and my fantastic daughters' Line and Elvira, for all their support and love.

Finally, my wife Beata deserves the biggest recognition, for the endless support she has given me through the ups and downs of the journey. For being my eternal sunshine and for providing me with perspective to my work.

David Rylander
Gothenburg, October 2021

List of Papers

This thesis is based on the following papers.

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 (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 (ISARC), Montreal, Canada, (p. 92-101).*

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, 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, Detroit, USA, (p.1115 – 1120).*

V Rylander, D., Fryk, J., Axelsson, J., Wallin, P. (2016) A Lean Speed Optimization Applied to a Cyclic Haul Operation*, World Mining Congress, Brazil.*

VI Rylander, D., Axelsson, J. (2021) Design and Evaluation of a System of Systems Architecture for the Optimization of a Cyclic Transport Operation*, 16th International Conference of System of Systems Engineering (SoSE), Västerås, Sweden, (p. 114-119).*

VII Rylander, D., Axelsson, J., Wallin, P., Cedergren, S. (2021) Characteristics and Models of Cyclic Earthmoving Operations for Lean Automation and Optimization, submitted to an international research journal.

Additional Publications

Related publication of the author not included in the thesis

i Rylander, D. (2013). System for calculating desired estimated time of arrival, *(U.S. Patent No: 10,019,012)*

Contents

I
Thesis

1. Introduction

The construction industry is a large and competitive business where quarries are a vital source of raw material. In Europe alone, there are over 26 000 quarries with an annual demand of 3 billion tons (UEPG, 2021) – delivering aggregates, sand, asphalt, and cement to different customers such as road construction sites heavy infrastructure, and buildings. As much as 35% of the produced material from quarries is used by road and road infrastructure construction, including bridges and harbors (UEPG, 2021). The main purpose of a quarry is to extract, e.g., rock, sand, clay, or gravel aggregates. The aggregate products may be further processed into e.g., cement, asphalt, minerals such as iron, and coal (The Institute of Quarrying, 2021). In the construction domain quarrying is a significant consumer of energy and producer of greenhouse gas. In quarries, transports consume about 30% of the energy and are the primary source of greenhouse gas emissions (Siami-Irdemoosa & Dindarloo, 2015). The ambition and purpose with the research presented in this thesis is the definition of an information system artifact that fulfills utility, is useful and improves the organization's productivity and decreases the environmental impact from earthmoving transports in the road construction and quarry domain.

1.1. Quarry operation

The U.K. legal definition of a 'quarry' is “a site of mineral extraction without a roof” (The Institute of Quarrying, 2021). The quarry is also known by other names as “surface mine” and “open pit”. The quarry consists of a set of sequential and potentially parallel subprocesses that can be referred to as work steps and that are required to produce the output products, see Figure 1. The work steps either process or transport material. In a solid rock quarry, blasting is usually required to get the right fraction of material for crushing facilities. For other materials such as clay, dirt, or aggregates, digging can start directly from quarry face and crushing may not be needed. In between work steps there may be buffers or stocks, commonly involving stockpiles or silos. Each work step is performed by one or many machines. These work steps are dependent of each other since each sequential subprocess is relying on the deliveries of the preceding subprocess.

For a quarry operation the transport process is one of the most changing and varying subprocesses. The destinations and routes used for transports change continuously as the mass are removed and processed. The transport process or parts of it can in some cases be done using conveyor belt or with loaders when short distances are applicable. When longer distances are required, earthmoving dump trucks are commonly used. A transport work step includes the load, haul, unload and return haul activities. A transport work step's overall capacity depends on loading and unloading capacity and its availability (input and output to the subprocess). Simultaneously there is a low tolerance of delays in the production. The overall production of the site is often depending on the uptime and deliveries of the transport work step. Significant downtime in the transport operation causes loss of production for the entire site. Such loss is a considerable higher cost than the benefits achievable by limiting waste in the transport process. Therefore, operative waste reductions need to be at a level where there still is a low risk of production loss effects from operative changes and variations.

The transport work step in a quarry is defined by a set of activities that can be described using a Value Stream Mapping notation (VSM) (Liker, 2009). In Figure 1 the quarry VSM including the main process steps are described with the most common material buffers (B) in between. The four main activities can be described as Load material, Haul Material, Unload Material and Return Haul to load area destination.

1.2. Lean Thinking

In the manufacturing industry, Lean production is a well know and utilized philosophy invented by Toyota (Liker, 2009) a.k.a., Toyota Production System or TPS. Womack and Jones (2003) describe Lean production as "do more with less". Quarry operation is similar to manufacturing industry with its sequential process steps. For this reason, it should be relevant to use Lean thinking in quarry operations with the ambition to increase efficiency and do more with less.

Lean is often considered a philosophy of continuous improvements to remove waste and optimize operations. 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 (Womack & Jones, 2003). 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 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 through the production process (Liker, 2009). 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 mapping, the different process steps and information flows within the production are identified and measured. 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 are very important. This approach is especially applicable when analyzing a value stream. Wastes (or "muda") are identified by actions and tasks that consume resources but do not add value to the product.

The seven original Lean wastes can be summarized as follows (Liker, 2009):

1. *Overproduction*: Producing more or earlier than the next process or the customer needs.
2. *Inventory:* A build-up of material or information that is not being used.
3. *Waiting:* Waiting for materials, information, or decisions.
4. *Movement:* Excess motion or activity during task execution.
5. *Transportation/Conveyance:* Moving material or information from place to place.
6. *Defects/Rework:* Production of defects or fixing an error already made/repair.
7. *Overprocessing or incorrect processing:* Doing unnecessary processing on a task or an unnecessary task.

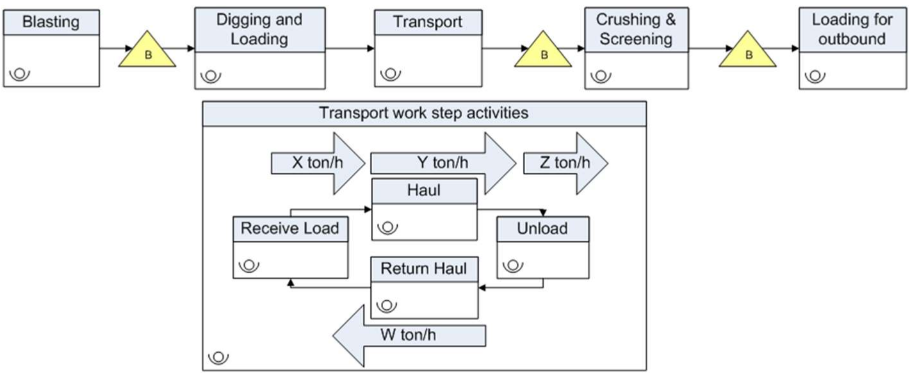

Figure 1. Main activities for quarry operation.

An additional eighth waste often reported is underutilized skills, which causes loss of time, ideas, skills improvements and learning opportunities by not engaging or listening to your employees.

The throughput of a production system is limited by the sub-process with the least throughput, referred to as the bottleneck. A bottleneck constraint is described by the theory of constraints (Goldratt, 1990) as “any resource whose capacity is equal to or less than the demand placed upon it”. In a dynamic environment the production rate and capacity of a subprocess varies over time, which may move the bottleneck.

Takt-based production is often used when the production is repetitive in cycles (Liker, 2004). 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 are 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. 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 subprocesses.

To address improvements in productivity its beneficial if it can be measured. The productivity and efficiency can be measured in different ways (Motwani, Kumar, & Novakoski, 1995). Productivity can be defined as the ratio of the input of an associated resource to real output (in creating economic value) (Dozzi & AbouRizk, 1993). The rate of production, e.g., ton/h or tonkm/h is usually a good indicator of productivity as long as the resource input costs over time are constant. Efficiency can be described by the value that is produced per effort added. In this work we look at efficiency related to “doing things right” and productivity a combination of efficiency and “doing the right things”, sometimes referred to as effectiveness. Highly efficient systems produce comparably large values with little effort. The waste in a highly efficient system should be small. For this reason, the amount of waste measured is an indicator of the efficiency of the system.

1.3. Site Optimization and Machine Control

The transports can be optimized and controlled with different perspectives. These perspectives can be divided into a hierarchy of strategic, tactical and operational planning and control (Axelsson, 2018; Moradi-Afrapoli & Askari-Nasab, 2020). The perspectives differ in time horizon, measures and actions that can be taken to address improvements, see Figure 2

The strategic level includes long term investments and decisions, such as investments in purchasing or development of equipment, processes, and tools. Such decisions can include which geographical area to operate in, what products to prioritize or what machines to develop or buy. The strategic perspective commonly has a time horizon covering years.

The tactical level focuses on the configuration of the resources at hand. Tactical plans include decisions on which resources to use including, staff, machinery, fleet and equipment that should be included in each operation. On the tactical level we find the overall balancing of the amount and size of machines to be used during an operation. Tactics include maintenance plans of machine and infrastructure. Tactical plans are commonly on the level of shifts, days and weeks.

The operational plan is often referred to as fleet management or as fleet dispatching techniques (Alarie & Gamache, 2002). The operational perspective also includes machine control. Dispatching can be described as a technique that include the control and decision of the next mission, destination, and route

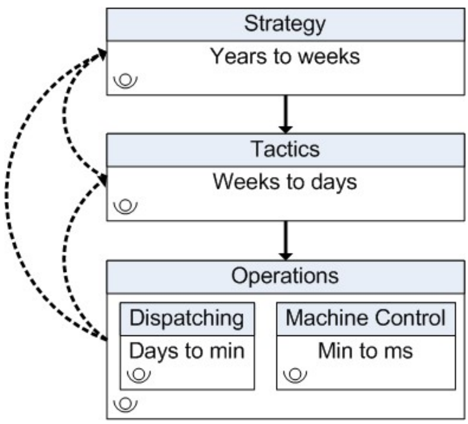

Figure 2. Levels and time horizon perspectives for site optimization and control with information feedback loops.

for each machine. The machine control perspective includes the detailed maneuvering and speed control of the machinery. The operational perspective can be down to millisecond or even nanosecond-based control loops.
In any production system including sequential processes and activities, there exists at least one bottleneck (Goldratt, 1990). While the maximum production is achieved, the overcapacity available in non-bottlenecks can be used to minimize operative costs. In a stochastic system, the strategic and tactical plans can only be optimized to some extent. For an operational plan, when a fleet of vehicles, routes and drivers is decided, the main possibility of minimizing cost relates to energy consumption. The main operational target is to maintain the required productivity (ton/h) with the assets available. Thus, cost optimization efforts need to manage risks of decreasing production, affecting the bottleneck and, consequently, the site's productivity. Therefore, changes in the operation need to be identified and managed to prevent loss in production capacity. While turning operational wastes into, e.g., decreased speed and later arrivals to destinations than what is theoretically possible, trade-offs for production loss risks and energy optimization need to be considered.

To optimize and control speed of a machine either by an assistive function or by an automated system, the design parameters to configure and execute the operation need to be known. To design and choose optimization and control algorithms, the characteristics of the parameters need to be modelled based on reliable data. For this purpose, it needs to be known what parameters to consider and what boundaries, variation, and dependencies the parameters include. Finally, as the environment is changing, the optimization and control approaches need to be dynamic and real-time.

1.4. 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. As the focus of the work is on mobile machinery, wireless communication is required. 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 awareness 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. As bandwidth have increased in recent years the main challenges for usage of satellite communication for real-time control have been identified as relatively high latencies as well as system costs (Handley, 2018). Liu, Prince, and Wallsten (2018) estimate latencies for consumers to 300–600+ ms (milliseconds) for satellite based communication in household environments. For cellular communication the bandwidth is rather high, but the coverage may not be guaranteed in remote or obstructed areas at all times. The latest developments within cellular technologies, such as 5G, include higher bandwidths, lower latencies, edge computing (Shi, Cao, Zhang, Li, & Xu, 2016) and network slicing (Foukas, Patounas, Elmokashfi, & Marina, 2017) technologies which all improve the possibilities to facilitate needed wireless communication for the real-time control of the construction and mining operations. 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. As it is the services available and decided by the network operator in the region of interest that define the cost and availability, there is no guarantee that the wireless communication needed is available in the region of interest.

As a complement and competitor to long range communication technologies, there has in recent years been an attention on research activities and product launches for dedicated short range communications (DSRC) based solutions in the road vehicle domain (Zeadally, Javed, & Hamida, 2020). Within this work there is an area of wireless communication called Vehicular Ad Hoc Networks (VANET) (Hartenstein & Laberteaux, 2010), which has a promising potential to address the needs of the 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.

Local DSRC communication does not require 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 (Rappaport, 2009). 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 (Rappaport, 2009). A number of standardized protocols are available on the three frequencies including the ubiquitous IEEE 802.11 (a.k.a. WiFi) (Stallings, 2005). 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 propagation (the signal bounces off its environment and several replicas of the same signal reaches the receiver). For this reason, there are also obvious limitations with the DSRC technologies even if it is free to use without a license.

1.5. Systems of Systems

Within the system engineering domain there is a sub-field called system of systems (SoS). System of systems is a research area that focuses on a the complex system problems that can be categorized by their principal characteristics of operational independence, managerial independence, evolutionary development, emergent behavior and geographical distribution (Maier, 1998). Operational independence and managerial independence are identified as the two main distinguishing characteristics for applying the term systems of systems. A system of system is often considered as offering more functionality and performance than the sum of the constituent systems. Several methodologies and patterns are described including a terminology (Axelsson, 2019) and taxonomy (ISO/IEC/IEEE, 2019) within the field. A significant architectural pattern description is the authority relationship within the SoS, which have been categorized by different types, referred to as archetypes. The archetypes include the Directed, Acknowledged, Collaborative and Virtual types (Dahmann, 2014; Maier, 1998). The existence of a central authority system can be referred to as a keystone and needed support systems as mediators. Participating independent systems are referred to as constituent systems.

Within construction and mining it is common with cyclic transport operations. A cyclic operation can be described as a transport mission which is iterated, and where a fleet of vehicles share the same mission to move a defined quantity of material from e.g., A to B. Vehicles in these conditions are typically earthmoving machines such as articulated haulers or rigid dump trucks. Different earth materials (bulk) need to be moved from one position to another and the total amount of mass to be moved is shared between the machines. Similar situations exist within harbors and terminals (e.g., Ro-Ro) but then not necessarily bulk. Instead, the mission may be to move a large number of containers or trailers. Similar cyclic transport characteristics also exists in other construction operations such as cement production and the road asphalt construction processes. The fleet of vehicles used may, for different reasons, not consist of the same type, brand and age. From case study observations, we know that the fleet may also consist of vehicles owned by different contractors. How the operation is governed varies in between enterprises and sites. Some sites own and operate their own fleets, but contractors and subcontractors are commonly used. Trucks and truck operators may be supplied by different enterprise on different conditions. In addition, trucks can be of different types, age and brand. To optimize and coordinate the operation it requires a system that can fetch and communicate data including a vast number of parameters from the different entities in the system. This system challenge fits all the principal characteristics of the SoS research area. The need for defined SoS mediators and potential existence and purpose of central authority systems is relatively unknown. The ambition and purpose with the research presented in this thesis is the definition of an information system artifact that fulfills utility, are useful and improve the organization productivity and efficiency.

2. Research Scope

In this chapter the motivation of the research is explained. The motivation and its challenges and principles are used to formulate concrete research questions that are addressed by the research performed. Further the chapter explains the overall research methodology used to address the questions, its validity and reviews the literature related to the subject.

2.1. Motivation and Scope of the Work

The construction and mining industry can be described and characterized by its sequential process steps as described in Section 1.1. This characteristic is similar to the manufacturing industry. Within the operation, there are transport processes where multiple machines share and collaborate on the same transport mission. As the machines and vehicles utilized may be of a different type, configuration, and age they can have different capacities. The material to transport, especially considering raw stone material often consists of an uneven mass volume, density, and weight. An additional factor is the operator skills and ability to obtain an even rate. These aspects cause an uneven capacity and production over time resulting in operational fluctuations which will result in Lean wastes if not controlled. This indicates a large potential for productivity, efficiency, and energy improvements, which motivates research activities within the construction and mining segments. A key hypothesis is that it should be possible to obtain a wanted production pace with a minimum of effort e.g., energy consumed leading to increase productivity. The approach of the research is that Lean thinking and system of system perspective provide a key standpoint to address the challenge.

The scope selected for this thesis is the transport operations within the road construction and quarry segments. The main reasons for including the two segments are that:

- These segments are connected in the production chain since the quarry and aggregate sites produce the raw material used in road construction and maintenance.

- The machines and equipment used for transportation, such as excavators, wheel loaders and haulers are present in both segments. Therefore, a supplier and owner of machines and equipment benefit if the technologies and applications are interoperable and compliant towards both segments' needs and processes.
- The quarry and aggregate and road construction segments 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. For this reason, both Lean thinking and production theory should be applicable.

2.2. Research Questions

The research in this thesis is based on the observation that construction and quarry operations are sequential processes like a manufacturing plant. Transport operations are then viewed as a subprocess in a workflow among other processes and should be dimensioned and balanced towards the entire workflow. Well-known manufacturing techniques such as Lean thinking address this problem but have not been fully explored with the aim for real-time control of transportation activities within mining and road work operations. In dynamic environments with stochastic variation and deviations using discrete machines, an operation without continuous control can be assumed to include Lean wastes such as unbalanced workflows, unnecessary buffers and waiting. Based on this assumption the first research question can be formulated:

Research Question 1: What kind of Lean wastes exist for transports within mining and road construction operation? (Paper I, II)

Typical operational wastes identified include that earthmoving machines wait at loading, unloading and narrow road segments due to meetings. The cause of the waiting can either be unbalanced workflow or due to operational deviations. A control mechanism could potentially optimize the operation towards just in time deliveries. Such a solution requires investments in control technology and its supporting systems and processes. To understand the value and the potential in developing and introducing such technologies the second research question can be formulated.

Research Question 2: How much can productivity and efficiency be improved by minimizing the wastes identified? (Paper IV, V, VII)

The main costs of the transport operation include the machines, operators, and energy. In a strategic and tactical plan the number of machines and operators can be minimized which then can improve efficiency without losing productivity. But as machines and operators are discrete, they cannot be divided to reach a non-discrete target. At some point the minimum number of machines and operators are obtained but the operation can still include wastes. In this situation the energy can be minimized by finding the minimum energy consumed to reach the target throughput. To be able to minimize the energy for an operation with the constraint of a target throughput the operational characteristics need to be known. Based on this reasoning the third research question can be formulated.

Research Question 3: What are the operational characteristics of a cyclic transport operation? (Paper VII)

The operational characteristics can be described with different perspectives as the optimization and control of the operation can be performed on different levels. Strategic, tactical and operational levels are often used to categorize the perspectives (Moradi-Afrapoli & Askari-Nasab, 2020). They include different time horizons and require different measures (see Section 1.3). All perspectives need to have an understanding of the operation, its environment and machine behaviors, characteristics, and parameter relations The behavior of one machine in a cycle and the time available to perform tasks depend on a large number of parameters, including machine internal, from the process and the environment characteristics. For this reason, a system design and architecture are needed to implement the control and optimization applications for the different perspectives. This leads to the fourth research question.

Research Question 4: What system design and architecture are appropriate for the functional and non-functional requirements identified? (Paper I and VI)

In a dynamic and harsh environment, there are several challenges. One specific challenge is wireless communication. The machines are mobile, hence wireless communication is required. The environment is reconstructed as the earth is blasted and moved. The sites are often at remote locations, in a deep pit, or underground. To facilitate control, it can be assumed that reliable and available wireless communication is needed but not always facilitated by existing mobile networks. The latest developments in mobile technologies allow for edge computing and local networks with dedicated base stations but this is still a relatively expensive and complicated solution based on the availability and investments from local telecom operators. The road vehicle industry has started utilizing dedicated short-range communication for vehicle-to-vehicle communication with similar needs for coordination as the presented use cases. This leads to the fifth and final research question.

Research Question 5: How can dedicated short range communication be utilized for the realization of the use cases? (Paper III)

The five identified research questions have been the goal of the work and guided the research activities performed. In some papers, each research question has been broken down into several research questions. The research conducted has utilized a research methodology presented in the next section.

2.3. Methodology

The main method used in the research is identified as design science research (Hevner & Chatterjee, 2010) through iterative improvements and empirical studies. This design science paradigm seeks to extend the capabilities of humans and organizations by creating new artifacts. Design science researchers seek to create innovations that define the ideas, practices, technical capabilities, and products through which the analysis, design, implementation, management and use of information systems can be accomplished. This methodology describes well the ambition and purpose with the research presented in this thesis as the target is the definition of an information system artifact that fulfills utility, is useful and improves the organization productivity.

Venable, Pries-Heje, and Baskerville (2016) present four steps for the design science research methodology which has been used in the research presented in this thesis. The four steps are: (1) explicate the goals of the evaluation, (2) choose the evaluation strategy or strategies, (3) determine the properties to evaluate, and (4) design the individual evaluation episode(s).

The goal is represented by the research questions addressed. The evaluation strategies vary between the papers. The decisions for which strategy to use have been based on the characteristics of the research question. The overall strategy has been to perform empirical research to the largest possible extent.

Most studies make use of inductive reasoning, but deductive reasoning is also utilized in paper I and VI to address RQ1 and RQ4. These papers utilize the general impressions and data collected to reason logically about the use and potential of the use cases, system design and system architecture.

Paper II, III, IV, V and VII can be classified as “Inductive” and applied since the real world individual case studies used, never can be a representation of all individuals at all times. The method is considered as “applied” since we are working on real users and real systems, in real world operation. The aim when utilizing “inductive” strategies 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 logical reasoning about the conclusions can be made. The main data source is empirical as real site operations have been observed and real machine and operational process data have been collected. In addition to the quantitative data, qualitative data have been collected by site operation observations, interviews, and questionnaires. The qualitative data collection involves different stakeholders and site operations in the construction business including machine operators, operation managers, and equipment suppliers. Quantitative data have been collected by equipping machines with data loggers of different kinds to collect machine sensor data. Overall, methods used vary depending on the research question characteristics and vary in between the papers, see Table 1.

2.4. Validity

The level of quality in planning, executing, and evaluating research is measured as validity. Considering the absence of a definitive criteria for how to accomplish validity it is proposed to address several measures of validity (Lucko & Rojas, 2010). This chapter first presents the types of validity relevant to this thesis. Then, each research question is discussed based on the identified relevant validity measures.

Relevant Types of Validity

Based on the characteristics of the selected research methodology, different methods can be used to evaluate validity. For real world research, Robson and McCartan (2016) conclude that a measure needs to be reliable, otherwise it cannot be valid. Further they divide the validity into the areas of construct, internal and external validity.

Reliability is the stability or consistency and repeatability with which we measure something. Unless a measure is reliable, it cannot be valid. The measure of reliability includes if the work is biased or include measurement errors.

Construct validity is concerning that a research effort is measuring what it is supposed to measure. Construct validity can be addressed by having multiple sources of evidence or by establishing a chain of evidence. Non-statistical methods contain the confirmation of skilled practitioners that the research and the environment where research is conducted are valid. The latter is also known as face validity.

Table 1. Research methodology applied to the research questions.

	Step 1: Explicate the goal of the evaluation	Step2: Choose evaluation strategy	Step 3: Determine the properties to evaluate	Step 4: Design the individual evaluation episode
RQ1	What kind of Lean wastes exist for transports within mining and road construction operation?	The strategy involves a combination of qualitative and quantitative methods where value stream mapping has been used. The techniques included stakeholder interviews and time studies.	Lean wastes identification including, overproduction, waiting, inventory and transportation.	The evaluation includes primarily Value stream mapping analysis. Several case studies have been performed where different operations in different countries have been observed.
RQ2	How much can productivity and efficiency be improved by minimizing the wastes identified?	Quantitative machine data collection from relevant operations. Strategy includes both controlled environments and uncontrolled real world operations.	Energy/fuel consumption based on driving characteristics (speed, acceleration, stops etc.)	The evaluation primarily includes operation scenario energy cost analysis.
RQ3	What are the operational characteristics of a cyclic transport operation?	To cover different aspects both qualitative and quantitative measurements have been utilized. Data from machines in real operation have been used in combination with observations, time studies and interviews.	Process configurations, activities, routes, time, distance, energy, mass (tonnage), speed, acceleration.	The evaluation primarily includes transport operational data analysis from real world operations.
RQ4	What system design and architecture are appropriate for the functional and non-functional requirements identified?	As the architecture differences are depending on the non-functional aspects, qualitative reasoning strategy have been used.	SoS archetype applicability, design pattern pros and cons analysis for relevant non-functional requirements.	The evaluation includes a logical reasoning about the potential of adopting technologies to the construction domain. Qualitative methods involving stakeholders though workshops and interviews have been performed.
RQ5	How can dedicated short range communication be utilized for the realization of the use cases?	The strategy is to perform quantitative measurements in relevant and controlled environments to cover identified scenarios repeatedly.	ISM bands difference in Packet Reception Ratio (PRR).	The wireless communication performance has been evaluated using real-world quarry environments as well as controlled environments.

Internal validity addresses the conclusions of the study. Internal validity is related to causality which determines the relationship between a cause and effect. In real life studies, it is common that multiple variables interact with one another, many of them uncontrollable or unpredictable. To address internal validity in case studies, we need to understand if the execution of the study somehow caused the outcome.

External validity is related to the concept of induction and focuses on the generalizability of results for prediction purposes (Leedy & Ormrod, 2005). To generalize from a sample, the sample must be representative of the population. To address external validity in case studies, proof can be taken from successful replication or generalization logic.

Assessment of Validity per Research Question

Lucko and Rojas (2010) argue that validation always depends on the specific purpose of the research. For this reason, we argue that each research question needs to be discussed separately. This section discusses the validity in the approach taken for each research question.

Research Question 1: What kind of Lean wastes exist for transports within mining and road construction operation? (Paper I, II)

To address RQ1, quantitative studies collecting various relevant data from different sites have been conducted. This was combined with qualitative studies using interviews to understand the site operation.

Regarding *reliability* we use different methodologies. For the initial and broad quantitative data collection made we utilized video cameras. One of the benefits of using this method is that we could collect the data without involving operational staff at the sites including the machine fleet operators. For this reason, it is unlikely that the results are biased due to behavioral changes from the data logging procedure. Interviews were performed with site managers prior to the logging to understand if the operation was typical or if there were conditions in the operation that were unusual. The aim was to collect samples from normal working conditions. No reporting of known unusual operations used in the samples was collected.

Construct validity is addressed by the method used where the whole or relevant parts of the operation was studied. The main source of evidence was video recordings, and the analysis was made using time studies based on the activities identified in the data. In several places, multiple cameras were used simultaneously to cover all relevant areas. This holistic view provided a very good overview of the reasons behind the wastes identified as all physical phenomena such as waiting and meetings at intersections can be identified and reasonably well understood.

To address *internal validity,* interviews with stakeholders and operational managers were conducted. The interviews sought to find out if the operation included in the study was representative of their normal operation and if the operation was reasonably representative of typical operations in the industry.

To further establish *external validity*, several sites have been studied, where the sites differ in size, and geographical location including different countries and continents. The sites are owned and operated by several different enterprises and utilize different brand, age and types of machinery. But even though the sample selected and used is diverse we cannot exclude that there exist other wastes that have not been identified in the studies. We cannot argue that the wastes identified even apply to all sites, but as some phenomena were identified in all sample sites, we argue that it is very likely that it is a common and relevant phenomenon in the industry. The magnitude of wastes in time and reoccurrence are likely not representative of all sites, instead they depend on the situation for when they were measured.

Research Question 2: How much can productivity and efficiency be improved by minimizing the wastes identified? (Paper IV, V, VII)

As the Lean thinking approach involves theory of constraints, flow-thinking and just-in-time principles, an approach to address the bottlenecks is to adjust speed to minimize costs for operation with unchanged production pace. This hypothesis is based on that speed affects energy consumption. To address the research question, several studies have been conducted. Initial tests include experiments in a controlled environment. Complementary tests from real world operations indicate similar results. As a group of studies, they provide evidence on the waste optimization potential including energy savings.

The *reliability* was addressed by calibrating the measuring equipment. Digital measures from machine internal sensors have been used but also physical measures including a specific tank measuring the actual fuel added and consumed for each test scenario iteration in lab environment. In real world tests the participants were uninformed about the general purpose and were instructed to operate the vehicle as usual. This approach can include participant bias, but as the results are complementary to lab tests the collective conclusions are not severely affected by participant bias. Further in the real world operational tests, the data logging was installed for several weeks which decrease the participant error and possible bias effect.

To address *internal validity* the first tests were construction in a controlled environment. Different scenarios were created based on the results from RQ1. Each experimental test scenario was iterated several times. External influences were minimized as the machines were pre-heated, the comparable data sets were logged during comparable conditions, including the day, weather conditions, route, path surface conditions and operators/drivers. Further validation in real operation has been performed where relevant datapoints have been analyzed for the same purpose using the same methodology.

Regarding *external validity* the scenarios are based on the general phenomena identified in RQ1. The measures collected are taken from specific but typical machines used. The absolute values of improvements cannot be generalized to apply to all machines, operations, or sites. Further the example scenarios used represent specific phenomena. How often the phenomenon occurs and the conditions for its effect on the improvement potential should be considered as unique for each operation. For this reason, the measures presented can only be used as an indicator for improvements and savings of the specific phenomenon and operations in general.

Research Question 3: What are the operational characteristics of a cyclic transport operation? (Paper VII)

To measure the operational characteristics for the purpose of control we need to have detailed data and models about the operation.

To address *reliability,* the data collection method used the machine internal sensors through an on-board logger which is considered sufficiently reliable and accurate. Further the data was collected for several weeks. Continuous monitoring of the data collection was performed to ensure quality in the data and to identify any errors. Further, measures were performed in the data analysis to detect abnormal deviations and patterns for possible identification of faults or errors. The data were collected at a high data rate (10Hz) to ensure that detailed events and deviations were recorded.

To address *construct validity* in the research the site used for the detailed measurements can be considered as a typical operation like many other sites observed. The data was collected for several weeks showing similar patterns. In addition, the characteristics identified are consistent with literature and with the other less detailed observations, e.g., while addressing RQ1 at other sites.

To address *internal validity* in a context where the environment is dynamic and complex our approach is not to find a universal model. Instead, a method was sought for how representative models of the operation can be built in real-time. For this purpose, a multiple regression analysis was performed to investigate how well a model can be created based on existing machine internal sensors. Relevant checks for multicollinearity and statistical significance were conducted in the analysis.

To address *external validity*, we conclude that the models provide correlation and statistical significance for the operation and machines studied. We do not claim that the results or models are generic for all machines, operations or environments regarding parameter values. However, since different topographies were used it is likely that the method would provide similar results in significance and correlation of the models if reused in other conditions. Changes in sensor accuracy or sampling frequency are likely to affect the performance of the method used.

Research Question 4: What system design and architecture are appropriate for the functional and non-functional requirements identified? (Paper I and VI)

Regarding *reliability,* the main methodology used involved qualitative reasoning including stakeholders. To address the system design challenges both functional and non-functional requirements were collected and analyzed. The requirements identified are based on the work while addressing the other research questions. The alterative architectures described are based on and likely limited by the system of systems archetypes. The result of the evaluation is likely influenced based on the thoughts, priorities and background of the stakeholders involved. To increase validity the suggested design was implemented and successfully tested in real world operations. Qualitative assessment through interviews and questionnaires with the operators were conducted.

Construct validity was addressed by using multiple sources for the assessment. The system design and architecture were evaluated and assessed by key stakeholders, implemented, and tested in a realistic transport mission scenario utilizing real machines and real material to transport. Further the system was evaluated by real operators that tested the system.

Regarding *internal validity,* the design patterns and potential architectures identified are based on the system of systems archetypes. The method chosen may limit the design diversity as it cannot be excluded that other design patterns exist. Anyhow the research conducted contributes with important aspects based on the patterns identified including the different tradeoffs that are needed.

With respect to *external validity,* the requirements for the design were based on the observations, interviews, and data collected from the different real world operations observed, and hence the results can be expected to be valid for a large part of the operations existing. Anyhow, it cannot be excluded that there are sites with fundamentally different requirements.

Research Question 5: How can dedicated short range communication be utilized for the realization of the use cases? (Paper III)

To address the research question, we choose to perform a quantitative study using experimental tests. A reason for this is the lack of reliable environment models for quarries in relation to wireless communication for ISM bands.

To address *reliability* the measurement equipment was configured using link budget calculations based on technical specification of the equipment and maximum allowed transmission energy for each frequency band used. HW/SW pre-tests were performed in lab environments. If the tests would be re-done in the same environment with the same specification of equipment similar results can be expected.

Construct validity is addressed by testing in several scenarios providing complementary results. Further the site used was identified as a representative sample similar to other quarry sites observed. The test scenarios used represent different environmental characteristics identified in quarry environments. The scenarios included both controlled and naturalistic environments, with and without obstructed line of sight. In the naturalistic environment, rough topography with dynamic line of sight was used. This was constructed by including test scenarios both on top, on the surrounding roads of the pit and in the bottom of the open pit.

Regarding *internal validity* there are several threats that can influence the conclusions. In wireless communication, interference is an important aspect to consider. However, as the areas used in the test are remote, few buildings, vehicles or people were present, and hence it is unlikely that the systems were affected by significant interference from external systems. Further the HW was separated, and the ISM bands used do not overlap. Also, several iterations of each test were performed. Due to the characteristics of differences observed in the study it can be concluded that the deviating factor is mainly based on the environment. Based on this, it is reasonably unlikely that the test equipment or test procedure had any significant effect on the results.

To address *external validity* specific identified scenarios were constructed to simulate different quarry relevant conditions. The conditions were identified during the observations at sites while addressing RQ1. Finally, additional measurements were conducted at a real world quarry site. Unfortunately, every site can be different so the results cannot be assumed to be applicable to all sites. But the scenarios tested, or at least some of them, are relevant for most operations. The limitations identified need to be considered in any design using ISM bands in the construction and mining domain.

2.5. Related Work

This section provides an overview of related work. The related research is grouped into the following categories:

- Lean Construction and Mining which covers the transition and use of Lean manufacturing to the construction and mining segments.
- Transport Planning and Fleet Configuration which covers the strategic and tactical plans of the operation.
- Transport Operation which covers the different aspects of operational real-time optimization including earth moving machine dispatching and automation.
- Systems Architecture and Wireless Communication which covers the challenges and related work within mobile machinery system integration including wireless communication and its interfaces.

Lean Construction and Mining

"Lean Construction" is an established research field with a broad perspective involving the different areas of buildings, bridges, railways, roads etc. involving the phases of architecture, engineering and construction (IGLC, 2021). The domain is much broader than the scope of this thesis but includes the field and share the philosophy.

More explicitly Jørgensen and Emmitt (2008) explored the transfer of Lean manufacturing/production from the Japanese manufacturing industry to the construction sector. They conclude that the focus of Lean so far has been on the system design, planning and management rather than on waste elimination. For this reason, they identify a need of aspects that seem to be overlooked, like the waste identification in operation.

Lööw (2019) published a literature review of Lean Mining and conclude that the principle of waste elimination seems most suitable for implementation and that it seems that the mining industry is ready to at least begin its journey towards Lean Mining. Further, Lööw (2019) investigate how the mining industry has implemented and practices Lean production. He concludes that "Lean production has not seen a full implementation in the mining industry."

Kahraman (2015) concludes that mining operations often are designed and managed around bottlenecks but that contrary to common belief in mining, bottlenecks are not static. For this reason, the author stresses the importance of identification of bottlenecks in real-time and how it will help also tactical and strategic level decisions. A bottleneck identification model is suggested to detect and rank the bottlenecks in the system.

Transport Planning and Fleet Configuration

In the category of transport planning and fleet configuration, there are two perspectives or time horizons where it is used. These can be described as strategic and tactical planning and their related decisions (Moradi Afrapoli, Tabesh, & Askari-Nasab, 2019). In strategic planning, the overall decisions are often based on the business plan and objectives. Measures can include the procurement of new equipment based on sales and production prognoses. For the transport operations, the fleet configuration is an important aspect where the total cost of ownership (TCO) (Ellram & Siferd, 1998) is a relevant measure to consider in the decisions for investments and procurements for how to reach a specific target. Investments are mainly made on future scenarios where characteristics of the site need to be modeled. These include the wanted production and capacity. The estimated capacity needs to be designed from environments that are estimated and predicted. For this reason, strategic decision support tools are often based on simulation of models. The general question is: "How many and what type and size of machines are optimal for the operation?" This question can be asked both from a strategic perspective where procurements are in scope and for tactical decisions in large operations where fleet configurations can be changed and/or altered in between different processes. The common approaches to optimum haulage fleet sizing are the match factor method and discrete event simulation modeling (Moradi Afrapoli et al., 2019).

Examples of such simulations are presented by Fu and Jenelius (2013) who describe a fleet performance simulation system where various fleet combinations can be analyzed considering a set of qualitative and quantitative decision variables. In their terminology, quantitative variables refer to the number of equipment units while qualitative variables capture the properties of the equipment, such as model and capacity. The developed simulation system uses discrete event simulation techniques to model the underlying earthwork operation with a given set of equipment, and to evaluate the performance of the operation in terms of transport efficiency. The simulation is based on detailed dynamic machine models combined with world models of expected routes. The authors present a GPS tracker method for how route data can be collected for simulation purposes (Fu, Jenelius, & Koutsopoulos, 2016). Validation of the simulation in real earth work operation was not presented.

The same approach of fleet performance simulation using discrete event simulations was successfully utilized to perform TCO calculations by Uhlin (2012). The TCO calculations include owning costs and operating costs. The fundamental problems to perform accurate simulations are identified as accurate models for the quarry transport process. The model needs to include the accurate pace of crushers as well as models for working machines in terms of fuel consumption and cycle times. Validation of the simulation in real earth work operation was not presented.

Validation of fleet configuration and TCO estimations and plans are complicated to achieve as they in reality can span over several years. Hoła and Schabowicz (2010) conclude that it is a major problem to accurately determine and plan the productivity of machines working in sets in earthworks execution. They discuss that it is mainly due to the random characteristics of operational parameters. Further they conclude that researchers often find that the actual productivity in earthworks is considerably lower than the theoretical productivity values.

The characteristic of the capacity balance in-between loading machines (shovels) and haulers (trucks) is often referred to as over or under trucked operation. An important measure of this is the "match factor" as defined by Morgan and Peterson (1968). The match factor ratio for homogeneous fleets is defined as:

$$\text{Match Factor} = \frac{(\text{number of haulers}) \times (\text{loader avg. cycle time})}{(\text{number of loaders}) \times (\text{hauler avg. cycle time})}$$

A complementing heterogenous match factor equation is presented by Burt and Caccetta (2018). What can be concluded is that the haulers and loaders are discrete leading to an unlikely perfect match. Further both equations are based on average cycle times which may include a large stochastic variance in activity times that influences the actual productivity of the operation.

Burt and Caccetta (2018) present many variables that affect the configuration of a site operation and fleet used and present approaches for how to manage them. They also categorize the solution approaches for fleet configuration presented in the literature into "Linear programming", "AI", "Heuristic", "Simulation" and "Queueing" based methods. 89 papers are characterized into the different areas. They conclude that satisfactory robust solutions are missing from the literature. Based on case studies presented in the study they conclude that high variation in production is best dealt with through high heterogeneity, a fleet with mixed sizes is more flexible to changes in demand than a fleet where all the machines have the same size.

Transport Operation

When strategic and tactical decision are made, resulting in a defined fleet and routes for a production, the operation phase is initiated. The operation optimization and control levels can be categorized as Dispatching and Machine automation. As the fleet is already defined, the remaining parameters to optimize are utilization efficiency, productivity, and operating cost including energy consumption.

Dispatching

Dispatching is a technique to dynamically allocate transport tasks to equipment fleets in order to improve efficiency, productivity and operating costs (Mirzaei-Nasirabad, Mohtasham, & Omidbad, 2019). A transport task can be described as a mission with a mass origin, destination, route, and schedule. After mission fulfillment the question of "Where should this truck go now?" is raised (Moradi-Afrapoli & Askari-Nasab, 2020). The general approach is to maximize utilization of available trucks and shovels in the system at any given time. The dispatching problem can be categorization as explained by Alarie and Gamache (2002) into:

- The m-trucks for 1-shovel dispatching problem.
- The 1-truck for n-shovels dispatching problem.
- The m-trucks for n-shovels dispatching problem.

Different authors have presented different solutions based on the problem characteristics. Further dispatching techniques can be categorized into solution approaches where two main categories have been identified, namely single and multistage approaches.

Single stage approaches simply dispatch trucks to shovels according to one or several criteria without considering any specific production targets or constraints. They are often heuristic methods based on rules (Tan & Takakuwa, 2016). A rule can be to minimizing shovel waiting time, minimizing truck cycle time, or minimizing truck waiting time. Munirathinam and Yingling (1994) conclude that results from literature show that the best rule is highly dependent on the characteristics of the mine in question. As several authors suggest, there may be utility in strategies that combine multiple rules.

Multistage approaches divide the dispatching problem into subproblems or stages. Chaowasakoo, Seppälä, Koivo, and Zhou (2017) performed multistage simulation experiments based on GPS data from actual mine operations including uncertainty in the dataset. Comparisons of the different problem strategies are assessed. The experiments of this paper illustrate how the choice of the dispatching approach impacts the production and argue that a multistage solution is superior. The simulation studies discover significant differences in production figures under different dispatching strategies. The *m*-trucks-for-*n*-shovels” provide significantly higher production even when unpredictable events are included in the model.

At smaller sites it is common that there is only one shovel with is served by one or several trucks. In large operations, it is the opposite where several shovels and several trucks are used. In those cases dispatching techniques have shown to have a significant impact. Mirzaei-Nasirabad et al. (2019) present a case study of transportation in the Sungun Copper Mine. The improvement of the total production with the best multistage dispatching method used was over 38% compared to the current mine production plan.

The dispatching techniques as explained in the overview of Moradi Afrapoli and Askari-Nasab (2019) include the primary objective of optimizing productivity and efficiency with the resources available. In our literature search we have not found claims that dispatching removes unbalance in the workflows or remove queueing as a result of stochastic behaviors and unbalance. The quarry operation often changes over time by its nature of removing material, leading to longer routes, longer travel times resulting in a changing match factor over time.

Earthmoving machine automation

In the earthmoving machine automation domain, the aim is on controlling and optimizing the machine operation towards its mission. The main focus is either on the trucks, the shovels including wheel loaders and excavators, or the crusher facility.

There is an area of work on optimizing a crusher facility where the main task is to keep production on a desired level and to protect the crusher from overload and fatigue failures (Bhadani, Asbjörnsson, Hulthén, & Evertsson, 2020). The work shows how key performance indicators (KPIs) defined by ISO (2014a) can be used to identify improvement opportunities for an aggregate production plant. The KPIs selected include equipment utilization, availability, and throughput rate, but the research is limited to four primary units in aggregate production: crusher, screen, bin and conveyor. Other equipment, such as material handling trucks and loaders, are excluded in this work.

Dadhich, Bodin, and Andersson (2016) identify the key challenges in automation and tele-operation of earth moving machines and provide a survey of different areas of research. They conclude that fully autonomous systems for the loading procedure that can perform equally well as manual operations are still far-fetched based on the current state of the art. Instead, it is argued that manual operation with technical assistance of loaders will continue to be the norm for a foreseeable future. This means that transport operation optimization should continue to consider manually operated machines and their behavior as its primary loading procedure for the years to come, even though the haulers may become autonomous. Autonomous loaders are expected to have lower cycle time variance than manually operated ones.

Regarding operator variability, driving studies have concluded that fuel consumption is heavily dependent on driver skills (Frank, Skogh, Filla, Fröberg, & Alaküla, 2012). 80 operators were used in an empirical study on operator behavior to identify the potential for fuel and productivity improvements. The variance in fuel consumption can be increased by as much as two to three times when comparing a novel and expert driver in certain driving conditions, machines, and applications.

Guevara, Arevalo-Ramirez, Yandun, Torres-Torriti, and Cheein (2020) identify that there are several variables, of which the amount of moved, loaded, and unloaded material are the main operational targets. The paper proposes a point cloud approach to estimate the effective payload volume for loaders. Volume estimations are central but need to be correlated to the density and shape of the material. For a transport optimization application, the variations in loader short cycle times and volume/weight are important for arrival time estimations. For that reason, this variability data is needed, and current research does not present such data in relation to a transport work step operation.

In addition, numerous simulations have been presented that compare different approaches to control drivelines through terrain and trajectory predictions and intelligent gear shifting. Fu and Bortolin (2012) obtained a decrease in fuel usage of 3.11% as compared to the current gear controller without increasing travel time.

Controlling the speed of a production process includes lowering the speed of machines and haulers towards the throughput and bottlenecks of the site. By lowering the speed of mobile machines, several values are obtained such as increased safety, decreased maintenance, decreased wear on tires and machine mechanical components such as engines, and decreased fuel consumption.

The amount of productivity gains that can be obtained is not trivial and depends on several factors. White et al. (2018) present indicative productivity gains from vendors of around 40% and potential cost savings of about 25 to 40% using Automated Machine Guidance (AMG) technologies. They conclude that contractors have a more conservative view of the gains that can be obtained using AMG.

Albrektsson and Åslund (2018) used a human interface to provide speed optimized advisory feedback to manual hauler operators. The optimization utilized a Pareto front of cycle time vs. fuel consumption for the speed optimization of the haulers. In the test, a 9% fuel efficiency increase was found when comparing the optimized mode with the cueing baseline. The system did not consider disturbances. They conclude that the operation includes a lot of disturbances/deviations in the loading time that had a significant effect on the outcome. Further, they conclude that a system that can effectively calculate loader cycle time with a narrow definition of actual loading and unloading zone is needed to manage the disturbances or real world operation.

System Architecture and Wireless Communication

Wireless systems for safety at the work site have been presented by various authors (Chehri, Farjow, Mouftah, & Fernando, 2011; Henriques & Malekian, 2016; Niu et al., 2007). The focus is on sensor networks in underground mines which have very different characteristics compared to open-pits including its solid rock material coverage, limitations of paths and possibility to mount wires for electricity and communication in the infrastructure. Chehri et al. (2011) perform a simulation of a mine with the purpose to perform environmental monitoring though utilization of wireless sensor networks based on Zigbee IEEE 802.15.4. The performance presented is measured in delay, throughput, and packet error rate.

Boulter and Hall (2015) conclude that "Most current wireless networks in open pit mining is based around the 802.11 family". Due to the harsh environments of open pit mines, the working environment is unpredictable and uncontrolled where fluctuation in temperatures, rain, vibration, humidity, chemicals, electrical shock, pressure, and physical damage may affect the normal operation of the platform or even render the platform inoperable. Further they state that the importance of wireless communication will increase due to the introduction and use of dispatching and automated vehicle technologies. They conclude that the design of a wireless network for any given mining site must be thoroughly analyzed for the requirements of that particular site.

Almeida et al. (2018) present an empirical study of radio propagation models for use of two frequency bands (700 MHz and 2,6 GHz) in open-pit mines. Data and evaluation from two iron-ore mines are used. They conclude that the Standard Propagation Model provides an accurate path loss prediction, but it requires complex calibration. To achieve reliable results, it requires not only a map but detailed information about the material in the mine. Their proposed model decreases the calibration complexity considerably.

Garcia et al. (2016) propose a framework that integrates mine and radio network planning so that continuous and automated adaptation of the radio network becomes possible. Further they conclude that the literature provides very little in terms of radio propagation in open pit mines. There is a need of mobile infrastructure with the purpose of self-planning and self-deployable communication infrastructure to adapt to environmental changes in the mine.

Ostroukh, Vasiliev, Kotliarskiy, and Sarychev (2019) discuss the new telematics standard AEMP/ISO 15143-3 for data exchange between mixed fleet machines and proprietary systems (ISO, 2020). A large number of applications and use cases are discussed including onboard weighing, proximity warning, machine health monitoring and fleet management systems that are expected to become increasingly used thought the adoption of the new standards. They conclude that one reason for the industry's poor productivity record is the continuous use of manual pen and paper based, physical tools. How the new standards fulfill the needs of real-time control and machine automation applications is not discussed.

Axelsson, Fröberg, and Eriksson (2019) investigate the interplay between SoS and constituent system architecture in a case study. The case study covers the construction process flow from the quarry to ready paved road asphalt. The main perspective is the interoperability and adaptivity of the system influenced by industry 4.0. The authors found industry 4.0 concepts useful, but adaptations including the less directed SoS compared to manufacturing are proposed. Most of the results are presented as generic and on SoS level. The need for more detailed work to describe the architecture of the SoS and the constituent systems is identified.

Summary

To summarize related work, we learn from Lean Construction and Mining that there is an identified potential to focus on waste elimination in operation. Methods to collect, identify and process real-time data is needed due to the characteristics of the operation where bottlenecks may move over time and takt time change.

Within the Transport planning and fleet configuration domain there is a need to understand and model the key characteristics in the stochastic behaviors and dynamics in the environment to improve the fleet configuration methodologies.

Transport Operations have come very far in the dispatching technologies, but we have not found any dispatching algorithms that include the real-time sensors or optimize energy consumption based on real-time machine sensor data often used for machine internal actuator optimization such as gear selection. A Lean approach to transport operation optimization and related productivity and energy optimization potential has not been found in literature.

Systems architecture and Wireless Communication conclude that detailed architectures describing the constituent systems and their relations are lacking. Further there is limited knowledge of radio propagation from the different wireless technologies available.

3. Main Contributions and Included Papers

The following sections present a brief description of the contribution from each paper. The papers are presented in the order in which they have been published, which also gives an indication of how the research has progressed over time.

3.1. 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 presents 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 research presented is based on challenges identified from state of the art in VANET application developments. The challenges 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.

While implementing VANET technologies, the applications described identify the potential in increased productivity at a road construction site and how increased awareness of site activities impacts traffic and improved road safety. The basic consolidated architecture is shown in Figure 3. 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.

3.2. Paper II

The operation of quarry and aggregate sites is 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.

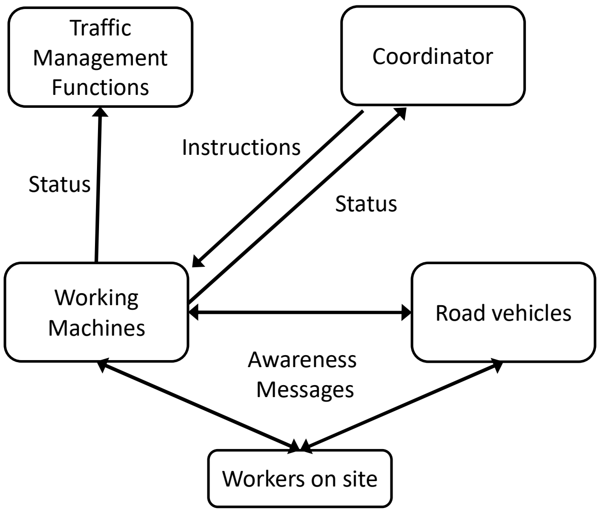

Figure 3. Road construction communication architecture.

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 4, from which data is obtained by time studies. The method presented includes four sequential steps, see Figure 5. The first step is to initially observe the site operation to identify the main processes and to create the VSM diagram for the site. Based on the VSM diagram, time studies can 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 provide the needed data for each activity which can be entered into 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 quarry 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, whose purpose is to feed the 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

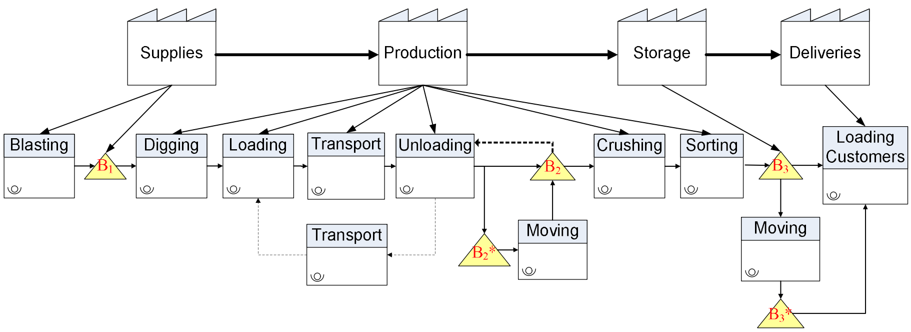

Figure 4. Quarry Value Stream diagram.

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.

3.3. Paper III

For geographically remote construction sites such as quarries there is a need of facilitating reliable wireless communication. Dedicated short range communication is a technology that has the potential to create vehicular ad hoc networks (VANET) to facilitate crash avoidance and for control and optimization of fleet movements. The road work topology is often 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 knowledge is very limited. 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.

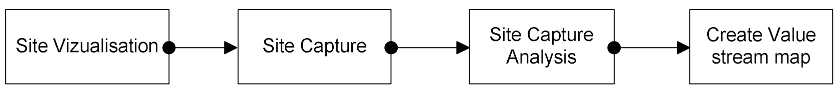

Figure 5. Site Capture Method.

The method used was to equip two vehicles with the technologies, define a suitable protocol to send direct packets, and log the packet reception ratio in a set of test cases. The test cases were 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, frequently communicating relevant data packages. 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 within a radius of more than 1500 m in beneficial conditions. Testing in obstructed situations showed significant differences between the frequency bands. Based on the results, a recommendation of using a combination of several technologies is stated as the best choice for the quarry, to simultaneously maximize range and throughput.

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

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

3.4. 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 methodology used in this paper was to perform a transport work using a relevant real machine over a relevant transport distance. The transport was performed with different operational characteristics including load and non-load and amount of stops during transport. 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 revealed 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 operation. Further the measurements include characteristics for driving fully loaded or without load at different top gears resulting in different top speeds and travel times. In addition, measurements are included for how rough topology affect the fuel consumption with different drive styles, and speed profiles.

It was determined that each stop per km added approximately 10% fuel consumption. 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 highlights 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.

3.5. Paper V

Cyclic haul operations are iterative transport operations, often performed by several haulers sharing the same transport mission. Cyclic haul operations are common in mining and quarry operations where the purpose of the haulage work step is to move mass a relatively short distance, e.g., from blasted rock supplies to the mass crushing and separation facility. The operation can include one or several haulers that perform the work simultaneously.

When several haulers are used, they are generally not synchronized in an optimized way and operative variations and changes continuously affect the operation. An example of such variations can be that the driving speed and time required for certain maneuvers vary depending on driver skills and machine capacity. An operative change can be that the loading position is moved, leading to changed routes and varying distances. The operative characteristics of the haul work step indicates that there rarely exists a static state that the operators can learn to do efficiently. Our previous research has shown that haul operations can have a fuel reduction potential of up to 42%, depending on the operation characteristics and wastes such as unnecessary stops and waiting.

This paper presents and assesses a system solution in a decentralized control system, see Figure 6 that calculates and advice operators with a speed for just in time arrival to a destination. The purpose of the system is to reduce fuel consumption with an obtained production rate. The system assessment shows that while production rate is obtained, fuel is reduced by up to 20% for individual machines, compared to base line operation in a simple quarry haul work step, including three haulers.

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.

3.6. Paper VI

Vehicles such as articulated haulers and dump trucks utilized in cyclic transport missions can be of different brand, type and have different performance characteristics such as engine power, traction, and load capacity. While utilized in quarry and mining operations vehicles may also be operated and owned by different organizations as they can be subcontracted to an operation. Based on interview and site studies the sub-contractor relationship between mining enterprises and transport and machine enterprises has been observed on multiple sites. The transport operation characteristics include stochastic behaviors and activity times that fluctuate over time, and hence real-time control is required for efficient optimization. As the vehicles are mobile, wireless

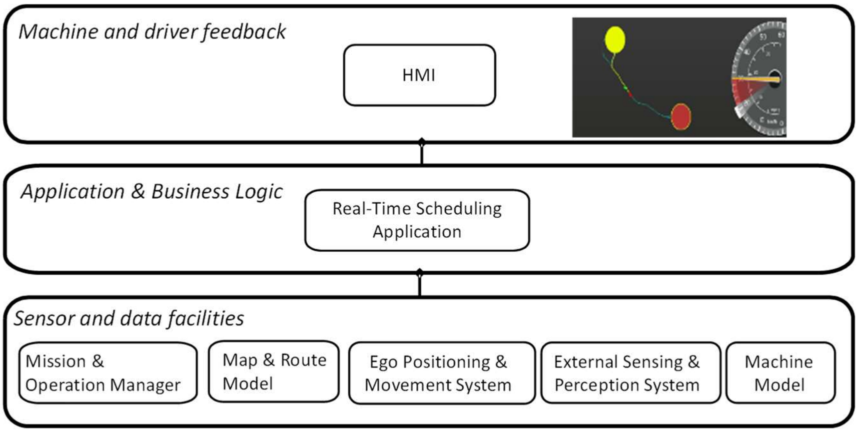

Figure 6. Machine internal SW component used in the study.

communication also needs to be available. As the characteristics of the constituent systems include managerial and operational independence, a system of systems approach is applicable.

This paper provides an overview of the key characteristics and requirements for such a system including the high level of logical components for the control system identified, see Figure 7. It discusses its components and identify three logical components that can be either physically distributed to vehicles or be hosted on cloud or server platforms.

The paper discusses the pros and cons of acknowledged and directed system architectures as described in Section 1.5 for the hosting of the control functions. The assessment focuses on the non-functional aspects of reliability, availability, scalability, security, maintainability, usability, serviceability, compatibility and life cycle cost.

Further, a case study is presented where an acknowledged system of systems is implemented in a real world mine and evaluated through a qualitative assessment of an operator assistive optimization system. Key findings include the drawbacks and characteristics of the architecture approaches. An assessment of SoS archetype design patterns using Pugh methodology (Pugh, 1981) resulting in a proposed Acknowledged architecture. Further challenges and

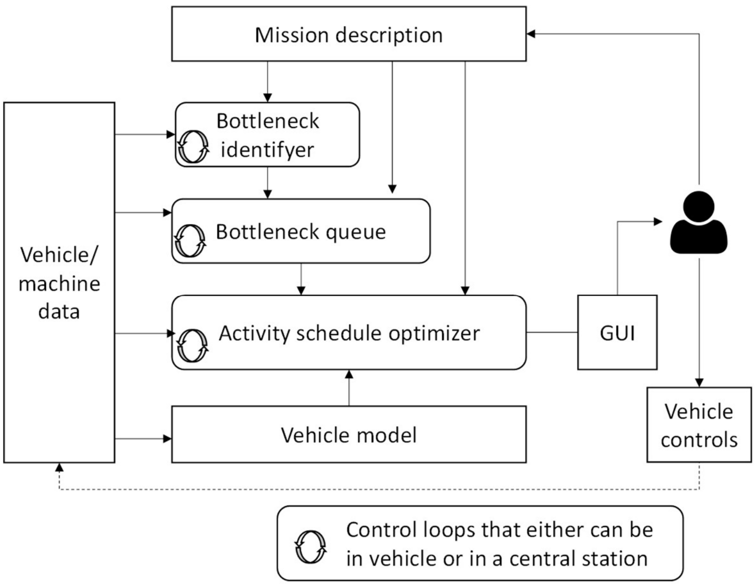

Figure 7: High level of logical components the control system presented.

potential for automation and production control of a larger process system are described.

My contribution: I am the main author of the paper and have been the main contributor to the data collection and analysis presented.

3.7. Paper VII

As presented in previous papers there is a large potential in automation and optimization of transports within quarry and mining. For this purpose, we have presented machine models based on pre-defined test environments where simple characteristics of energy consumption as a function of speed and amount of stops has been presented. What has been lacking is the operational characteristics description from real world operation and formal machine operation models. This paper provides insight into cyclic transports and the parameters that affect energy consumption and productivity. The method used has been to collect and analyses data from machines in real world operation and use the data to develop formal multi-regression models. The paper presents and discusses the characteristics of the operation identified, develops models for energy consumption and productivity, and discusses its usage for optimization and automation purposes.

The results include the identification and measure of stochastic fluctuations in activity times that need continuous real-time control for an optimization system to be effective. Formal regression models for cycle energy cost and hauler fuel rate are presented. The best models presented for fuel rate were achieved as a function of acceleration, slope, and speed using separate models for loaded and unload machines.

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.

3.8. Summary

The scientific contributions of this thesis can be summarized as follows:

- A Lean method to identify improvement potential in transport work steps
- Presentation of optimization use cases based on operative Lean wastes, including unnecessary driving, unnecessary stops and waiting.

- The description of environment characteristics and important system requirements.
- Identified synergies and improvement potentials in Road Construction.
- Assessed wireless short-range communication performance in target environment.
- Assessed the machine fuel consumption improvement potential in the identified use cases.
- Proposed, assessed, and demonstrated system architecture solution for site operation control and optimization through operator feedback.
- Presentation of operational characteristics of cyclic transport operations in quarry and mining.
- Presentation of models for transport operation optimization and machine optimization based on statistical analysis.

4. Results

In addition to the scientific contribution from each paper presented in Section 3, this section presents a summary of the results described in relation to the research questions formulated. Further, this section includes a discussion about the challenges associated with the implementation and applicability of the results while introducing autonomous machines and challenges in a system of systems perspective.

4.1. Results per Research Question

Research Question 1: What kind of Lean wastes exist for transports within mining and road construction operation? (Paper I, II)

Paper II contributes to how Lean principles and methods can be used to identify stakeholder needs and real-time improvement opportunities. A method is presented for how to use VSM analysis to identify operational wastes while collecting and using data from real world operations. The method proved to be successful and identified and quantified several Lean wastes for which real-time control is required as a system solution. The Lean wastes identified include unnecessary stops, waiting at both loading and unloading, and unnecessary transports/movements.

Paper I present improvements for road safety and quality of service. Three applications are identified where improvements in traffic flow and road work operation control can be addressed: traffic incident detection, road work information dissemination and road work operation control. The main targets in the applications are to reduce waiting times, traffic jams and increase operational productivity. An example presented in the paper is that compactors at a road construction site would benefit from synchronization with the overall process. Another example presented is that asphalt pavers would benefit from synchronizing their pace with the asphalt supplier system. The idea of the paper, even though not as explicitly stated in Paper I as in Paper II, is that Lean waste would be minimized with the presented examples.

Research Question 2: How much can productivity and efficiency be improved by minimizing the wastes identified? (Paper IV, V, VII)

In Paper IV we explore what the identified wastes from Paper II cost in energy consumption, and we present the relation and trade-offs between speed, travel times, non-value-adding stops, and energy consumption. The results of fuel measurements show a potential in fuel savings of up to 42% and a typical improvement of 20-30% depending on machine speeds, travel times, application and site characteristics.

In Paper V we demonstrate and discuss how important it is with real-time control as the activity times within the transport work step fluctuate stochastically. To control the operation, integrated technology with multiple sensors combined with reliable and available wireless communication is required for efficient control. The system assessment shows that while production rate is obtained, fuel is reduced by up to 20% compared to base line operation in a quarry transport operation, including three haulers

In Paper VII we use machine data for a more precise measurement of the different activities within a transport process. Activity times and energy consumption per activity is presented. The load maneuver time had the largest relative standard deviation of 51.8%. The loading maneuver activity time is the time from when a hauler reaches the loading area until the first load is received. This time includes the waiting time at the loading area, and it shows that significant waiting occurs at the load area. The paper presents the energy consumption per activity but also for the whole cycle. Looking at the full cycle perspective, the highest energy consumption was 10% higher than the lowest with comparable transport work performed.

Research Question 3: What are the operational characteristics of a cyclic transport operation? (Paper VII)

To be able to design an efficient control system to a problem the characteristics of the target environment need to be understood. For this reason, Paper VII presents the characteristics in terms of activities and states that the earth moving machines in the transport system can be in. Each activity is measured from real world operations, and the meantime for activity fulfillment is presented together with its standard deviation. The identified stochastic fluctuations in time consumed, speed profiles, and energy that the machines consume are discussed and specific measures of how different speed profiles and stops affect energy consumption are presented. The paper further presents models for energy consumption based on several parameters that can be used for control and optimization purposes.

Research Question 4: What system design and architecture are appropriate for the functional and non-functional requirements identified? (Paper I and VI)

In Paper I we present system architectures for improving road safety and productivity through increased situation awareness, sharing of road work data, and the real-time coordination of machines.

In Paper V we present and demonstrate a decentralized system architecture with main control loops on the machine level. We demonstrate with real machine implementations how it can reduce energy consumption in simpler cyclic transport work steps involving single load and unload positions with one route. We assess the productivity and conclude that a significant fuel reduction can be made in the scenario demonstrated.

In Paper VI we conclude that a system of systems perspective is needed, and we present different architecture alternatives for a real-time coordination and optimization system using SoS nomenclature. Further, we assess and analyze the different architectural patterns and suggest an acknowledged archetype for future implementation at scale.

Research Question 5: How can dedicated short range communication be utilized for the realization of the use cases? (Paper III)

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 using available ISM bands in challenging the application domain. Results from empirical studies include the packet reception ratio obtained while using the maximum allowed transmission gains for each frequency band. Different experiments were made exploring different scenarios relevant for the application, including measurements in a real world quarry.

4.2. Discussion

The research performed and presented in this thesis show the potential energy saving by introducing active control of the workflow to reduce Lean waste. The conclusions include the findings regarding operative Lean wastes from real sites and the demonstration of productivity improvements by implementing a control and optimization system. For this reason, it may seem strange that such solutions are not well utilized and available on the market. The main reasons can be divided into the complexity and characteristics of the operation as well as the data readiness and its interoperability.

The operational characteristics complexity can be summarized as:

- The sites move and change over time. In addition, the ground is processed and blasted which affects the paths. A continuously updated digital map is needed to schedule work and calculate and predict travel times. To implement an optimization system the environmental models for the operation need to be updated and available for the system.
- Construction sites lack reliable and predictable communication infrastructure and the business size and revenues as well as site flexibility affect the possibilities for installing and maintaining fixed communication infrastructure. Compared to the underground mining business, which regarding the activities and somewhat the equipment used is very similar to a quarry, the underground mines do not change the paths as often and the communication infrastructure is easier to maintain. The positioning underground is however technically different from the most common system used above ground based on satellite triangulation as GPS.

The data readiness (Lawrence, 2017) and interoperability (Axelsson, 2020) in the systems on the market is weak. The data that we have collected is based on deep insight into the machine sensors and behavior, which is usually exclusive to the machine manufacturer. In this research, access to data has been ensured through collaboration with Volvo CE as a manufacturer. All data that is based on machine internal sensors has been collected from the same brand. Mixed brand fleets are, for this reason, a challenge where standards need to evolve for this purpose.

When the needed data from machines is available, communication in between different machines and, in some cases, enterprises owning, and operating machines need to be facilitated. Recent development in the area of related system interoperability as the ISO standard 15143 (ISO, 2020) or ETSI (ETSI, 2014) does not provide all required data items or accuracy enough for the optimization presented in this thesis. Perhaps it cannot be expected, as the scope of the standardization did not include the use cases. Therefore, the prototypes built and presented required a definition of a proprietary protocol for the purpose of the research and is currently not available or supported for wider use.

Introduction of Autonomous Machines

The thesis introduces and demonstrates an assistive function where operators are advised for how to operate optimally, including speed profile. It is still the operator that controls the actuators. A further development could be to have an active speed control, like Adaptive Cruise Control also known as ACC (Marsden, McDonald, & Brackstone, 2001) or Cooperative Adaptive Cruise Control (C-ACC) (Van Arem, Van Driel, & Visser, 2006). Such a step would likely need to have a more precise calculation of the speed profile and need to manage sudden changes based on instant deviations. A speed advice can with a Lean perspective change from high speed to low speed instantly. In a graphical user interface such change can be presented directly but in the case of acceleration or retardation-controlled actuators it is probably wise to have a smooth transition. An active control system is likely to include security and safety in a different way in the system requirements compared to an advisory system where the human operator is responsible for the actions.

Fully automated machines are expected to lower the variance in operator behaviors since a robotic operator does things consistently. Several parameters are independent of the operator's skills and input as human operators have physical limitations and cannot see and adapt to what happens while obstructed. These need to be considered, and from the production flow perspective, the entire fleet operation still needs to be connected to avoid production loss and lower productivity and efficiency.

To successfully automate the operation, either through operator assistive functions or fully autonomous machines, e.g. SAE Level 4 (SAE, 2021), several factors need to be considered. Regarding operator assistive functions, it would not be possible to effectively assist the operators while only considering one hauler in a fleet of haulers. It can also be concluded that while in operations where multiple destinations exist and a sorting mechanism is performed by the loader, the loader also needs to be connected to such an assistive function. In some sites it has been observed that sorting mechanism are very stochastic as specific types of mass (e.g., larger stones or clay) may have a specific destination and other material another. This is very hard to predict as it may be decided or found while extracting the material from the face. Based on the variance and standard deviations presented, which is a consequence of the operation's fluctuations, continuous activity measurements and feedback loops are required. It may be possible to automate parts of the operation, but it would then be necessary to also connect the machines that are not automated to the system.

As the operation and its environment is dynamic machine learning and AI technologies can be a candidate technology to utilize. This then needs to have significant access to data and could potentially be used for both the strategic, tactical, and operational control and optimization. Further research is required on the architecture for how to integrate such technologies and what methods to utilize and where.

5. Conclusions

This section presents the conclusions of the thesis, as well as recommendations for future research.

Overall, the thesis shows that there is a large potential in reducing operational Lean waste in transport processes within road construction, quarry, and mining operations. The work is structured through the contribution towards the five research questions. The thesis contributes with identification and description of Lean wastes and improvement use cases for the road construction as well as quarry and mining segments. We have assessed and measured the identified potential in energy consumption, productivity, safety, and efficiency. We have measured, analyzed, and described the characteristics of the target operation and its environment for control purposes. Furthermore, we have presented machine and site energy consumption models for control and optimization. Likewise, we have presented, analyzed, and suggested system design and architecture solutions for the identified applications. We have built prototypes and assessed them in different environments, including simulations and real world operations. Finally, we have contributed with wireless communication infrastructure assessments based on DSRC.

Based on the results, we can conclude that optimization and control in the construction segment operations need:

- An SoS perspective as there are often multiple actors as vendors and mobile machine owners, multiple machine types, different machine life cycles, and varying machine capacity in the system.
- Availability of detailed and continuously updated machine and operational data.
- Detailed knowledge about the site characteristics and its dependencies to other processes and the environment.
- A control system needs to be in real-time as there are continuous unpredictable stochastic changes in the operation and in the environment. A pre-operational plan would include significant errors, as it cannot include the changes and fluctuations that occur.
- Available wireless communication networks. Sufficient coverage in a dynamic environment can be complicated to predict and maintain.

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. Based on the different business models, VANET can complement cellular based technologies for safety and awareness-based applications which do not require long range communication.

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. In sites with obstructed areas and large geographical coverage, base stations functioning as repeaters, extending range may be required.

Specific for the quarry and mining segment the included papers conclude that:

- Operational Lean wastes such as waiting have been observed for up to 33% of cycle time. The observations are based on real life operation observations using the Lean Value stream method and time studies.
- Reduced fuel consumption of up to 42% depending on waste characteristics and driving style has been observed through quantitatively obtained values from real machines operated in controlled testing environments.
- In real world operation individual machines differentiate the fuel consumption with 10% for complete work cycle. The value is obtained comparing normalized work cycles with highest and lowest fuel consumption for the comparable work.
- Stops due to meetings, intersections etc. have a significant impact on energy consumption. In real world operation, each stop during a cycle had an average energy cost of 1.7% of the entire cycle is energy consumption. This is a significant cost that can be reduced by either increased real-time control or infrastructure construction investments.
- Communication range using VANET with low packet loss was obtained for up to 1000 m in good environments but could in obstructed areas be measured to about 70 m. This shows that communication infrastructures using VANET need to be well designed based on the condition of the operation.
- Operators that have tested a prototype system for speed optimization through assistive functions in general find the application useful and informative for their daily work.

- It is possible to create models for machine energy consumption (fuel rate) as a function of machine internal sensor parameters acceleration, speed, slope and load with statistical significance and correlation.

On a system level, we have presented a control logic concept for a Lean based optimization of a cyclic transport operation for quarry and mining processes. We have discussed and assessed how the control logic can fulfill utility through the functionality required by different SoS archetypes, and design patterns. Based on the architectural assessment and validation we suggest an acknowledged SoS architecture design with centralized constituent systems.

We have implemented and tested a decentralized architecture for operational data and verified that its functions work and can save energy for simpler workflows. With a decentralized approach for communication of operational data, the system becomes less dependent on central communication infrastructure. A decentralized approach is based on peer-to-peer (P2P) communication also known as V2V in the automotive industry. In such a system, nodes such as machines can communicate without the need of an infrastructure node (e.g., base station, access point). A decentralized approach requires a well-defined protocol for communication. A decentralized approach for communication of operational data can be part of a central management system as a constituent system in a SoS. The main benefits of a central approach for CS are identified as improved security, maintainability, and reliability while compared to vehicles as constituent systems. The reason is that a central management system can monitor and maintain the system and detect faults and errors as well as respond to them.

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

5.1. Future Work

The main areas of future work include improvement in architecture, control, and models as well as further assessment, scaling, and usability validation of the approach and characteristics presented. The future work identified can be categorized into improvement of the methodology, deployment and commercialization as well as challenges while taking on a wider scope.

Methodology improvements

In the approaches presented there may be other methods to improve models and controls that would improve the results. Such methods include how machine learning and AI techniques can be used to identify, measure and optimize machine and operational characteristics. Future models should also consider variations in environment including temperature, moist and road traction.

An optimization system of mobile machinery in a dynamic environment is dependent on communication infrastructures that facilitate reliable connectivity with low packet loss. Future work includes the improvements in such infrastructure. An alternative solution is to utilize hybrid systems using VANET in combination with 5G technologies over multiple radio frequencies. Such a solution is a candidate to provide sufficient coverage. Further research for what methodologies and technologies to use is needed.

Deployment challenges

To further scale and deploy the suggested optimization solutions further work on assessments, industry acceptance and validation is needed. Not the least on the of system of systems architecture for how to create an interoperable solution using linked data including communication protocols considering the multi-brand and vehicle type and capacity variations (different sizes of machines). Future work needs to include the standardization of such a control system in a SoS context.

Wider scope

The scope of operation can be widened. A future scope should include alterative drivetrains, level of automation as well as other segments and operational characteristics.

The use of hybrid or electric drivetrains in the earthmoving machines may have different characteristics compared to conventional. Electric plug-in solutions are likely to have a significant effect on the daily operation as charging could be a reoccurring activity during shifts. Further these alternative types of drivetrains may have a different characteristic and change the models presented. Further parameters not included in the models such as weather, regenerative breaking and gear strategy may further improve the models presented.

Control strategies for how to plan, integrate and control such activities in relation to all other activities is a challenge that needs to be addressed. Especially if the charging stations are shared between different processes and possible brands and machine fleets.

The thesis demonstrates an advisory function in a graphical user interface, where the operators still control the actuators based on their own judgement. A future solution could be to integrate the solution in a higher level of autonomy where actuators are controlled by the system. A first step towards autonomous machines could be a Lean Adaptive Cruise Control (L-ACC).

The introduction of autonomous machines (removing the human operator parameter) may change the stochastic behavior of the operation. How this affects the characteristics of the operation needs to be further investigated. As the human operators can be assumed to perform coordination to some extent today as part of their work, autonomous machines can be expected to increase the need for optimization and coordination systems.

The work in this thesis focuses on the cyclic transports in confined areas in quarry and road construction. Further work is needed to include other segments and should consider the characteristics while utilizing public roads and a more unpredictable traffic environment. In such an environment it is unclear if the same type of speed adjustments are feasible due to, e.g., traffic rules and road safety.

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