RESEARCH REPORT

Lean Production in Mining

an overview

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INTRODUCTION

This report has been produced as a part of the I^{2}Mine (Innovative Technologies and Concepts for the Intelligent Deep Mine of the Future) project. I^{2}Mine is a European Union-project with the vision of realizing the concept of invisible, zero-impact mines. The main focus is on the development of technologies suitable for deep mining activities. However, the sixth Work Package – named *Health and safety and environmental aspects in future deep mining,* containing, among other, the tasks *Design criteria and guidelines for implementation* (Task 6.1) and *Evaluation of new production technologies* (Task 6.2) – has a focus on topics such as health, safety and organisation of deep mining.

As part of Task 6.1 of the I^{2}Mine project, a handbook aimed at mine planners will be produced (the recommendations from the handbook will also be incorporated into Task 6.2). The handbook's main purpose is to provide mine planers with guidance in designing safe and attractive work places. In doing this, however, the issue of organisation and management will always be encountered. As such, a section of the handbook will be dedicated to the organisation of the workplaces of the mines of the future.

A management concept that is not only popular, but also has seen success in the manufacturing industry, on the one hand, and the health care sector, for example, on the other hand, is Lean Production (LP) (Johansson & Abrahamsson, 2009). As future mining will be shaped in a context where it is necessary to produce at costs that are determined by international competition, and where long-term demand will increase (Hancock & Sinclair, 2008), mining companies, too, will begin looking towards LP to rationalise and increase the productivity of their business (and, to a certain extent, already has, as this report will illustrate).

While LP is not without critique (e.g. Carayon & Smith, 2000), other studies has shown its potential to increase both productivity and employee well-being, given that focus is spent on the appropriate factors (Conti et al., 2006; Hasle et al., 2012; Hasle, 2014; Westgaard & Winkel, 2011). Because LP both provides the tools for mining companies to flourish; is becoming popular; and shows evidence of being able to improve work environments, using this concept for the subject of organisation and management in the handbook, can be justified.

Despite this apparent interest in the concept, little research exists on the subject of Lean Mining (LM) – i.e. LP's application in the mining industry. As such, this report aims to summarise most of the research that does exist in the area. A thorough review will be conducted, where each paper will be presented in detail. The aim is to answer the questions below through analyses of the found papers:

- Have certain areas proved, or is theorised to be, more suitable for an implementation? In what areas of mining LP been attempted to implement?
- What results are argued to be obtainable and what results can be observed from the implementations (both long-term and short-term)?
- How was the concept implemented? What made the implementation successful or unsuccessful? What is suggested to be required for a successful implementation?
- What parts of the LP concept was implemented or is suggested to be implemented in the mining industry?
- Is the adoption of LP by the mining industry dependent on any certain developments, such as new technology (e.g. continuous mining machines for metal mining or *in-situ* processing)?
- Are there any characteristics unique to mining that hinders or helps in an implementation of the concept?

The report is concluded by looking towards future: How is the concept of LP to be turned into a concept of LM?; What modification of the concept is required?; And so on. In doing so, it is the intention of the author to provide the reader and the industry with a possible way forward; to provide a road map to LM.

Structure of this report

It is worth noting the structure of the result part of this report. The reviewed texts are grouped together by author (see the next section for details). The group names are also the names of the sections in which that group is covered. The source of all text in each subsection can be assumed to be from the author(s) in the given group – any deviation from this will be indicated. The information presented in each section should be available in any of the texts in the group; if it is only available from a specific text, this will also be indicated.

LITERATURE REVIEW

The majority of the articles were gathered through the use of the databases Scopus[1], Web of Science[2], and ProQuest[3]. The search terms used for each database together with the number of results is presented in Table 1.

In addition to the above databases, both Google Scholar[4] and the database search engine of Luleå University of Technology (LTU), Primo[5], was utilised. Because of the limitations of these search engines, the search procedure was less systematic, relying instead on the combination of a few different search terms for each search. One or a few search terms from each category in Table 2 was combined.

[1] http://www.scopus.com/
[2] http://www.webofknowledge.com/WOS
[3] http://www.proquest.com/
[4] http://scholar.google.com/
[5] http://www.ltu.se/ltu/lib?l=en

The results from the above described queries yielded a significant amount of irrelevant results. By reading the abstract and titles of the identified papers, it was, however, possible to easily distinguish the relevant papers from the irrelevant ones.

Table 1: Databases and search terms used, together with the number of results.

Database	Search term	No. of results
Scopus	("mining industr*" OR "minerals industr*" OR mining) AND ("lean production" OR "lean manufacturing" OR "lean mining" OR "lean thinking" OR "lean princples" OR TPS OR "toyota production system") AND NOT "data mining"	42
WoS	("mining industr*" OR "minerals industr*" OR mining) AND ("lean production" OR "lean manufacturing" OR "lean mining" OR "lean thinking" OR "lean princples" OR TPS OR "toyota production system") NOT "data mining"	13
ProQuest[6]	(Same as above)	191

Table 2: Example of search terms that were combined.

Category 1	Category 2
Lean production	Mining
Lean manufacturing	Mining industry
Lean thinking	Minerals industry
Lean mining	Underground mining
Toyota production system	Metal mining

Following the identification of the initial papers, the reference lists of these papers were reviewed in order to find additional articles. The reference lists

[6] For ProQuest, results were further narrowed by only considering texts that had been published in scholarly journals.

of any new articles were also reviewed, and so on. And, lastly, some unpublished texts and texts in print along with reports on LM were acquired with the help of the faculty of the division of Human Work Science at LTU. In total, 17 papers are included in this report. The texts reviewed in this report are presented in Table 3.

Grouping of the results

The material of some researchers has been published in more than one place, e.g. one report might serve as a base for a subsequent article; or an article published in one journal might have been shortened and published in another journal with a slightly different angle. These texts have been grouped together and will be reviewed together as well. The groups share the name of the author or authors. All papers are assigned to a group corresponding to the author, even if the group contains one paper. The group name is the name (or names) of the author (or authors) as it (or they) appear in the in-text citation. This is to aid in the presentation of the results and in keeping the review uniform. The groupings as well as all reviewed texts are presented in Table 3. All in all, this review includes 14 groups consisting of 17 texts.

Table 3: Selected texts and their groupings.

Author(s) and year published	Title	Type of text
Yingling et al., 2000	Lean manufacturing principles and their applicability to the mining industry	Journal article
Dunstan et al., 2006	The Application of Lean Manufacturing in a Mining Environment	Conference paper
Klippel et al., 2008b	Management Innovation, a way for mining companies to survive in a globalized world	Journal article
Klippel et al., 2008a	Lean management implementation in mining industries	Journal article
Wijaya et al., 2009	Implementing Lean Principle into Mining Industry - Issues and Challenges	Conference paper

Table 3: *Continued.*

Author(s) and year published	Title	Type of text
Bäckblom et al., 2010	Smart Mine of the Future: Conceptual Study 2009-2010 Final Report	Report
Hattingh & Keys, 2010	How applicable is industrial engineering in mining?	Conference paper
Haugen, 2010	Mine of the Future (MIFU) Work Package 4: Lean mining	Report
Steinberg & De Tomi, 2010	Lean mining: principles for modeling and improving processes of mineral value chains	Journal article
Sanda et al., 2011	Miners' Tactic Knowledge: A Unique Resource for Developing Human-oriented Lean Mining Culture in Deep Mines	Conference paper
Helman, 2012	Analysis of the potentials of adapting elements of lean methodology to the unstable conditions in the mining industry	Journal article
Shukla & Trivedi, 2012	Productivity improvement in coal mining industry by using lean manufacturing	Journal article
Ade & Deshpande, 2012	Lean Manufacturing And Productivity Improvement In Coal Mining	Journal article
Liu, 2013	Study on coal lean mining theory and practice	Journal article
Haugen, 2013	Lean mining	Journal article
Castillo et al., 2014	Implementing Lean Production in Copper Mining Development Projects: Case Study	Journal article
Maier et al., 2014	Adopting lean and characteristic line based industrial methods for optimizing room and pillar processes	Conference paper

WHAT IS LEAN PRODUCTION?

There is plenty of literature describing the concept of LP, its origin, how to successfully adapt it to your business, and so on. Arguably, among the most popular of these, and certainly the most relevant for this report, are the books by Liker (2004) and Womack and Jones (2003). Both books present models for LP.

Liker's (2004) model of LP consists of 18 principles divided into four levels, referred to as the 4P model. The model, including all principles, is presented below:

Long-term philosophy

1. Base your decisions on a long-term philosophy, even at the expense of short-term financial goals.

The right process will produce the right results

2. Create a continuous process flow to bring problems to the surface.

3. Use pull-systems to avoid over production. Let customer demand set production rate.

4. Level out the workload (*Heijunka*).

5. Create a culture of stopping to fix problems (*Jidoka*), to get quality right the first time.

6. Standardised tasks and processes are the foundation for continuous improvement and employee empowerment.

7. Use visual control so no problems are hidden.

8. Use only reliable, thoroughly tested technology that serves your people and processes.

Add value to the organisation by developing your people

9. Grow leaders who thoroughly understand the work, live the philosophy, and teach it to others.

10. Develop exceptional people and teams who follow your company's philosophy.

11. Respect your extended network of partners and suppliers by challenging them and helping them improve.

Continuously solving root problems drives organisational learning

12. Go and see for yourself to thoroughly understand the situation (*Genchi Genbutsu*).

13. Make decisions slowly by consensus, thoroughly considering all options; implement decisions quickly.

14. Become a learning organisation through relentless reflection (*Hansei*) and continuous improvement (*Kaizen*).

Another model is provided by Womack and Jones (2003). The five principles of the model can be described as it is below:

- *value* is only definable by the customer and only meaningful when expressed in terms of a product or service which meets the needs of the customer at a certain price and time;

- *the value stream* is the set of all required actions to produce the product and/or service;

- *flow* is what remains to be achieved once value has been defined and the most obvious wastes eliminated;

- *pull* is the concept that the customer pulls the product rather than the company pushing the production (once flow has been achieved); and

- *perfection* is the idea of involving everyone in the value chain to perfect the creation of value.

The first four principles (value, value stream, flow and pull) are described as principles that “interact with each other in a virtuous circle” (Womack & Jones, 2003, p. 25), with perfection encompassing it all.

The two models overlap and both of the above models will be of use in reviewing the texts on LP in mining. However, while each model has their own strength, and being familiar with them is important in understanding LP and its potential, they are lacking for the purpose of this report. This is because the model utilised by each individual author (or group of authors) differ throughout the reviewed texts; not only between one of the two models, but at times no clear model is used at all. As such, the model by Lyons et al. (2013) will be used when discussing the concept of LP in this paper. The model is based on the literature published on the topic of LP, i.e. the model presents LP as it is being used and discussed, as opposed to presenting LP as the concept is prescribed. The reasoning for choosing this model is explained by the authors themselves:

> The framework was not developed in order to make an unnecessary addition to the existing lean thinking framework-set. Rather, it provides a lean architecture that is not only suitable for this study by allowing the adoption of lean principles and practices to be readily established but also it provides a coherent, uncomplicated amalgam of those goals, principles and practices that are evident in the most authoritative lean thinking research. (Lyons et al., 2013, p. 478)

Because it is “capturing the sentiments of the published lean thinking literature” (Lyons et al., 2013, p. 479), it has the best chance of encapsulating the different aspects of LP as brought up in the reviewed texts. And, although not completely exhaustive or definitive, it is still “a representative lean model that can be utilised in a practical manner for determining the adoption of lean thinking principles and practices” (Lyons et al., 2013, p. 480).

The model describes LP as consisting of four *principles* which, in turn, consist of a number of *practices*. The principles are alignment of production with demand (e.g. pull systems, one-piece flow), elimination of waste (e.g. 5S, TPM), integration of suppliers (e.g. supplier development activities, JIT deliveries), and creative involvement of the workforce (e.g. *kaizen*, work organised in teams) (Lyons et al., 2013). The principles are not exclusive, however, and there is some overlap, i.e. one practice might be considered to be part of two or more principles.

The different principles and practices of the model still require further explanation. This will be briefly described in the following paragraphs. The descriptions below are based on both Liker (2004) and Womack and Jones (2003). Note that this summary of the practices does not encompass all practices of LP or of the above model. The focus here is on the practices that are included in this review.

The *alignment of production with demand* is the principle that deals directly with production. The idea is that products should be manufactured on demand instead of being "pushed" through the production – i.e. production is "pulled" based on the demand of downstream customers (both internal – e.g. other workstations – and external – e.g. people or companies buying the product). Production is started at signals sent from a downstream customer. Another way to express the idea is that production should be "make-to-order" as opposed to "make to stock". The demand of the customer sets the rate at which products are produced. This is usually referred to as *takt* time and is expressed as a ratio of available time per day over the demand per day. The result is how often a product would have to be finished to meet the demand.

The principle of production alignment also prescribes the ability to vary production rates, i.e. production has to be flexible. The concept of flexibility also involves the ability for machines and processes to be used for several different products (non-specialised equipment), and for changes in volume and product mix to be accounted for. Finally, there should be a commitment to reduce cycle times and a drive towards utilising minimum economic batch sizes.

The *elimination of waste* is probably the most recognisable Lean principles, and waste and its elimination are central concepts to LP. In total, there are eight different kinds of waste: (1) overproduction; (2) waiting times; (3) unnecessary transportation; (4) unnecessary processing or reworking; (5) inventories (e.g. intermediate storage); (6) useless motions; (7) scrap, repairs and inspections; and (8) unused employee creativity. To effectively and efficiently eliminate waste, commitment is required from the whole organisation. The mapping of these wastes and activities that increase the product value is referred to as value stream mapping (VSM).

Standard operations are required to provide instruction on how to best perform a procedure with as little waste as possible. It is also needed for evaluations, i.e. to determine if the task, production technology, or maybe even the whole flow, needs to be modified. To support in standardisation and in ensuring quality, visual control is utilised. This is usually in the form of information centres.

The principle also includes the establishing of systems that prevent faulty products from continuing in the production process; each worker is trained to recognise and control potential defects. Quality is also further ensured by adapting the concept of *poka-yoke* (meaning "idiot proofing" or "mistake proofing"). This entails designing technology and tools in such a way that it is literally impossible to make mistakes in positioning, number of operations, operations sequence, and so on.

Another tool included in the principle of eliminating waste is *Total Productive Maintenance* (TPM), which is sometimes referred to as "integrated maintenance". The purpose of TPM is to create disruption-free production by encouraging all employees to get involved and continuously making small improvements and preventative maintenance.

To lessen the waste associated with waiting, quick changeovers are strived for. *Single-minute change of die* (SMED) is a useful tool for this purpose. The tool helps in reducing setup-times, i.e. either the time to prepare for the production of each product, or the time required to make the changes required to produce a different product – or both.

Finally, there is *5S*[7]: a tool which objective is to engage every employee in all aspects of production and, with orderliness, create an efficient and conducive workplace. The aim is also to gain an overview and to make production, flow and any shortcomings visible so that improvements can be made.

The *integration of suppliers* entails actively supporting suppliers in their effort in becoming "Lean". This means assisting in solving problems and improving performance. The goal is for deliveries to be *just-in-time*[8] (JIT), i.e. deliveries should arrive exactly as they are needed in the production. The suppliers, like the ordering company, will have to be flexible, with the ability to quickly respond to changing demands. Furthermore, the aim should be to develop long-term contracts and relations between the supplying and ordering company. Through these long-term contracts, both parties can develop, and better align themselves to each other.

To conclude, there is the principle of the *creative involvement of the workforce.* In many respects, this principle concerns avoiding the eighth waste – unused employee creativity – however, it also deals with developing and training the workforce, as well as improving their working environment. The work should be organised in multi-functional teams, i.e. there should be no specialists – instead each member of the team should be capable of doing the tasks of the other team members. This not only makes the teams less sensitive to disruptions, but also allows workers to rotate between different tasks.

[7] 5S refers to the first letter of the words "Seiri", "Seiton", "Seiso", "Seiketsu" and "Shitsuke", normally translated as "sort", "straighten", "shine", "standardize" and "sustain".

[8] JIT is also often talked about in the context of production flow: products should arrive just in time at the next station in the flow.

Problem solving should also be team-based. The problem solving ties into the concept of *kaizen*, or continuous improvements, which is the idea that organisations should continuously strive to improve on ever last detail, i.e. to develop existing, stable and standardised processes in small steps. These, however, has to be worker-driven; it is the workers who possess the knowledge of the manufacturing process and its short-comings.

LEAN PRODUCTION IN MINING

An account for all texts that were identified will be given in this section. The order is chronological. In cases where a grouping includes text published over several different years, the latest published text will be used as a reference, as these latest published papers are assumed to be the most relevant or include most new findings.

Yingling et al.

The first article on LP and the mining industry was published in 2000 by Yingling et al. Its title is *Lean Manufacturing Principles and Their Applicability to the Mining Industry*. It is a theoretical study with some examples being based on author experience. Many of the subsequently published texts cite this article. The article, furthermore, represents one of the more thorough discussions of the application of LP in mining, providing examples from the whole value chain (from high to low level of the organisation, i.e. the relationship between suppliers and customer; to individual operations).

The authors begin the discussion with the topic of value definition, the importance of correctly defining value, and tools for doing so. Since the products of mining differ from products usually produced by "Lean companies", an example is provided to illustrate possible factors that might influence the value of the product:

> … a utility's desire that a coal be "easy to handle" might be translated to particular product specifications involving acceptable combination of moisture content, size distribution, and ash composition. (p. 218)

As such, the authors see no reason for why the application of value definition to mining should be any more difficult than its application to traditional manufacturing.

The topic of flow is covered next; four tools or practices are included in this: standardised work, quality-at-the-source, TPM, and flexibility/SMED. They are all discussed as being required for stability. The lack of stability is described as resulting both from, and in, machine breakdowns, product defects, and variable operating times – all which prevent continuous flow. Stability is, thus, a prerequisite for flow.

On the topic of standardised work, the authors bring up the point of mining and traditional manufacturing differing from each other. They note the concerns voiced as a "mine is not factory", and would therefore not be appropriate for standardised work. The authors argue that, although not perhaps as easy to implement as in the more stable environment of a factory, mining does not possess characteristics that would render an implementation of standardised work impossible. On the contrary, without standardised work there can be no potential for learning and improvement. They do note, however, that the standardised work would have to have higher flexibility than that of a factory.

The discussion then moves onto quality-at-the-source. What is essential to note regarding quality-at-the-source in a mining context is that the worker has less control over quality than he or she would in a factory environment, as illustrated by the quote below:

> Quality is largely a function of ore selection, it is impacted by many uncontrollable factors, and quality control is largely left to the beneficiation plant. However … [c]utting and loading procedures that minimise ore dilution would be valuable at any operation. (pp. 224-225)

They do, however, note that quality-at-the-source does have uses outside of product quality. Yingling et al. bring up the auxiliary work of ensuring safety, arguing that quality-at-the-source could be used to ensure that roof bolts are installed correctly, faces are only being worked under safe conditions, or that blast holes are being prepared properly.

For TPM, the authors state that, since preventive maintenance is already well established and widely accepted in the mining industry, the implementation of TPM should be of no difficulty. The utilisation of TPM should results in further improvements in maintenance, thus improving stability.

The discussion on flexibility relates in large parts to SMED. The discussion culminates in basically stating that reduced setup times are something to strive for. The differences of mining, as compared to traditional manufacturing, are, however, something that requires some change in how to approach the subject:

> In contrast to manufacturing operations, mining operations tend to be cyclic, with most setups occurring between successive cycles. A wise strategy often is to devise systems that increase the cycle duration and thereby minimise the frequency that setups are needed. (pp. 227-228)

The paper continues with the discussion of designing for flow and the difficulties in doing so in mining. While attaining flow in mining would indeed be beneficiary, the analytical techniques and "flow design tools" usually utilised in manufacturing, have little relevance in mining. The authors state that, presently, there are no well-established methods for designing for flow in mining.

This leads to the discussion of pull/JIT. Mines traditionally utilise push systems, but the authors argue that pull/JIT is possible to introduce to mining. In this, they note the importance of having the goal of balancing production to demand; to establish stable production processes that produce a required quantity at a given time. The biggest possibility for the implementation of pull/JIT seems to be for supplies and materials, however. Such an implementation would be straight forward:

> Kanban systems could be used to coordinate the flow of supplies simply and automatically throughout the mine … Such a system should be easier to manage than existing supply systems at most mines because of the simple information flow. (p. 233)

But broader application of the pull system at a higher level should also be possible. The authors argue that the application to transportation should be reasonable: trains, barges, etc. could be scheduled to arrive in a highly uniform manner to keep demand as level as possible.

The article also covers the element of perfection. To achieve perfection, many of the "teachings" of LP is said to be required (this requirement is not unique to mining). This, in turn, requires further training of the workforce, and permanent job security would essentially have to be offered. The biggest challenge for the implementation of "perfection" is said to be the changing of values and organisational culture.

Regarding the implementation of the concept, the authors have several recommendations. They state (in a manner similar to many other authors of literature on LP) that "it is important that lean be implemented as a total system for production process design and management" (p. 220). They also recommend implementing LP at a higher level of the value chain, instead of starting by focusing on the processes in the production.

As mentioned earlier, for achieving flow, stability in the production process is required. It is important to note that, even though flow is an element of LP, the stability required for the flow can be achieved with the tools of LP. It is, as such, not a requirement that the production processes be stable *before* LP is attempted to be implemented, as one of purposes of the many tools of LP is to achieve a stable process.

Another topic which the authors bring up fairly frequently is that of safety. In the authors' description of the concept they maintain that practitioners of the concept should seek to establish a safe, secure, and fulfilling work environment where workers can flourish. This picture is further reinforced when discussing standardised work, which is described as a procedure for performing the operation with minimum human effort and maximum safety. It is also brought up in the discussion of quality-at-the-source. The topic of safety is also discussed in terms of flexibility, where job rotation and multiskilling is recommended.

The final topic relates to competence. The authors promote continuous learning in LP organisations, arguing that all employees should be something of an industrial engineer (or at least be familiar with the industrial engineering principles), knowing the basics of time studies, ergonomics and being able to utilise basic analysis principles. They also make a case for a flexible workforce:

> Lean production systems seek a flexible workforce where each individual can man numerous operations and genuine teamwork is practiced (shojinka). This, of course, requires extensive cross training, but the investment is considered worthwhile … Here, one individual works multiple machines each production cycle in contrast to traditional practice to assign one individual per machine. (p. 227)

The general idea is that the workers should be cross- and multi-skilled as well as motived and encouraged to learn, and, perhaps most importantly, offered training.

Dunstan et al.

The Application of Lean Manufacturing in a Mining Environment by Dunstan et al., published in 2006, is a paper from a conference proceeding, which disseminates Rio Tinto's experiences in applying LP in a mining environment. The paper covers the implementation in several different areas, including aluminium plants. Since this report is concerned with LP in a mining context, the implementation in areas such as aluminium plants are outside the scope of this report and is therefore left out. The following summary will instead focus only on the paper's description of the implementation in mining.

The paper's first example of the application of LP in mining comes from a bauxite mine. Information centres (referred to as Lean Information Centres), 5S and standardised work are said to have been implemented. Only standardised work is described in more detail: the implementation was done in a truck service bay by challenging routes utilised and the layout of equipment. This reduced time taken for routine services (e.g. refuelling and checking tyre pressure) and was done by analysing the movement of trucks and people. This is said to increase the productivity by "at least one truck load over the crude ore dump per day" (p. 152). Standardised procedures were also defined, which led to a reduction in contamination of lubricants and oils by capping nozzles – an improvement that helped the company the company avoid production loss. Another improvement was to standardise the location where trucks were parked.

An underground mining example is provided from the experiences from a block-caving copper mine. The application of LP was focused on the developmental works of the mine. The first development in this effort was the establishing of Lean Information Centres. These centres tracked metrics such as safety, environment, employee availability, cycle completion times, weekly development targets and utilisation of resources (how these metrics were measured is not covered by the paper, however). These efforts are reported to have resulted in improved communication between team leaders and crew members, as they were then able to see where issues were occurring. Another effect is reported to have been that crew members were more willing to contribute to identifying and solving issues that caused delays in the production cycle. Other reported effects include a reduction in cycle time within the first 30 days of adoption.

A similar effort was carried out at coal mining site, i.e. information centres were introduced to the operation. The implementation seemed to have had a positive effect and might have been a needed improvement to the operation, as is made clear by the following quote:

> Prior to Lean's introduction there was no forum within [the organisation] in which operations, maintenance and planning personnel could come together to discuss issues across the mine. (p. 155)

The effect of this implementation effort was measured in the reduction of variance in the production plan. Exact figures are not provided to the reader, but it is clear a reduction has taken place.

At several places in the paper, prerequisites and preconditions for a successful implementation are mentioned. Among the first is the mention of the company's previous experience with Six Sigma, which required a "strategic, company-wide approach to business improvement … to achieve a sustainable culture change" (p. 147), which is also said to be required by LP. Furthermore, the authors also mention the need to implement LP to all their operations, not just the ones that resemble manufacturing operations[9].

Like the management literature on LP, the importance of the engagement of the managers is brought up at several occasions. The paper mentions both the need for managers to allow shop floor personnel[10] to solve problems and make operational decisions, and the need for manager buy-in and for their role to be that of a coach and a mentor;

> The manager's ongoing role is to be an equal contributor and a mentor who will clear obstacles to progress, providing necessary resources and challenging

[9] However, note that not all operations have been "subject" to an implementation – that is to say, only a few areas within the described organisation have gone through a Lean implementation.

[10] "shop floor personnel" is the actual term used by the authors; it is not entirely clear whether this also include mine workers, but, presumably, it does.

> the team to continually improve. Managers should also coach problem-solving. (p. 145)

The authors are also clear on the point that the production and its goals have to be made visual for employees to easily and clearly access data on performance and output. This is done via the information centres, which might account for the strong focus on said centres in the described implementation efforts.

The paper also mentions a bottom-up approach, with a top-down learning program. The learning program is attended by a vertical slice of the organisation to “ensure participation in and understanding of lean at all levels” (p. 152). This is also said to have helped with the implementation of LP.

This leads to the topic of competence, which is also mentioned at several points in the paper (including the quote in the above paragraph). On one hand, LP is described as playing “a key role in the personal skills and career development of all employees” (p. 155); and, on the other hand, LP is described as a tool for retaining skills in an era of high labour turnover:

> Lean provides a management tool through which operations can acquire or relearn the basic skills faster and in a more structured and sustained way. (p. 156)

Also related to the implementation of LP is the comparison between the mining industry and the automotive industry. These differences, as presented by the authors, are available in Table 4. Although it would appear that there are quite substantial differences between the industries, the authors state that there is nothing in the LP concept that makes it exclusive to the automotive or discrete manufacturing sector. They motivate this by stating that LP “has become a common and effective methodology in many other manufacturing, processing and service industries” (p. 145).

Table 4: Comparisons between resource/minerals business and automotive operations (Dunstan et al., 2006).

Resource and minerals business	Automotive business
A smelter or refinery cannot be stopped so there is inherent production push in the process	An automotive assembly line can be stopped so there is the ability to create pull systems
Production is in continuous units and around the clock	Production is in discrete units and often on less than one day cycles
Generates considerable dust	Little dust
Physically challenging environment	Ambient conditions
Inherently variable environment	Stable work environment
Remote locations	Large centres
Impact of weather[11]	Indoor environment
Inherently variable raw materials	Controlled raw materials
Geographically spread output teams	Compact plants
Molten metal has a short shelf life before it solidifies	Long-life components suitable for supermarket-style storage

Klippel et al.

This grouping includes two articles written by Klippel et al., both of which were published in 2008. The articles are named *Lean management implementation in mining industries* and *Management Innovation, a way for mining companies to survive in a globalized world*. Both articles have the same empirical base. The papers cover two case studies done in two Brazilian mines. Both studies consisted of mapping the production processes involved in two underground mining blocks. By involving the mine workers, improvements were found and implemented.

[11] Presumably this is only true for open-pit mines

The first case study was conducted in a fluorspar mine. The researchers mapped the operations and found that 46% of the operations were essential, 39% were auxiliary operations, and 15% were wastes. Among the causes for waste, reported by the researchers, was the fact that drilling and blasting operations were carried out by the same individual, who was in charge of both sharpening the drill and fetching explosives – during which time the drilling machine was idle. By adopting brainstorming, the decision was made to organise teams[12] of three drillers, where two performed the essential operations and one performing supporting ones.

Further wastes were caused by poorly designed and insufficient ventilation. Reducing these wastes included moving the ventilation controls and standardising the ventilation compressed air hoses. After the improvements were made, the operations in the block could be summarised as follows: 60% of the operations were essential, 34% auxiliary, and 6% wastes. According to the authors, the mining block showed an increase in productivity as well.

The second case study was conducted in an amethyst mine which employed rudimentary underground mining methods. After process mapping the operations in a pilot mining block, the operations could be categorised as follows: 46% processing, 3% transportation, 1% inspection, and 50% waiting. Among the wastes identified was waiting for dust to be ventilated. This was caused by the dry drilling technique utilised as well as an inefficient ventilation system. This was resolved by utilising a wet drilling technique and by upgrading the ventilation. The improvements resulted in the processing time accounting for 62% of the total operations time.

The second case study merits some further description since it brings up the health and safety of the worker. The change to drilling did indeed improve productivity, but, arguably, the biggest improvement was in the improvement in worker health. The dust concentration at the mine face was de-

[12] Organising people in teams might be viewed as an improvement in line with the Lean Production philosophy as well.

creased significantly, which will positively improve long-term worker health. It is unclear, however, if this was because of the LP principles of respecting people, the researchers' concern for the workers, or just a side-effect for the productivity improvement.

Wijaya et al.

The conference paper – *Implementing Lean Principle into Mining Industry, Issues and Challenges* – is by Wijaya et al. and was published in 2009. It provides a theoretical discussion of the potential of implementing LP and its principles to in the mining industry.

The most significant issue the paper brings up is on the topic of value. The authors state that, in the mining industry – and especially the base metal industry – both product and customer have unique characteristics. The products derived from the mining industry (ore) can be considered products that have well-defined, inherent specifications and requirements. Quality and the price are established by the market and there is little product differentiation between companies. Transactions seldom occur with direct contact between the mining company (as a product provider) and the buyer; most metals as sold to an exchange. As such, "direct" customers (companies that buy the product) do not play as an important role as they would in other industries. However, in a broader perspective, the mining industry has several indirect customers who – passively or actively – affect the business. They are stakeholder such as society, government and media. Their major interest is not necessarily the quality of the product itself, but rather the quality *behind* the product, e.g. the product's impact on environment, human well-being, and economic prosperity of the society. These interests represent part of the mining industry's current values.

The paper also accounts for sources of variation in the work cycle that, presumably, have to be eliminated or dealt with to enable, or at least aid in, a LP implementation. The operations and their potential sources of variability are presented below:

- During drilling, rock hardness inside the face is difficult to predict.
- In charging, the volume of the explosive gel might have variation.
- In blasting, unexpected results may be obtained due to unobserved rock formations.
- In mucking, the volume and speed of loading is dependent on the ore size, which might vary.
- In scaling, the volume of work is not known until work has been completed. For example, the number of lose rocks that require mucking is dependent on the rock formation.

The authors conclude that each of these activities result in the work cycle having high degree of uncertainty. The paper then goes on to describe the different tools and principles of LP and how a potential adaptation to the mining industry might occur.

Standardisation in mining is described as difficult due to the fact that much of the work is dependent on uncontrollable factors, such as rock movement. Variations in work can also be high, as different conditions need different ways of working. However, the authors argue that standardisation can be realised to some extent and provide the reader with the example of rock bolting: the number of rock bolts required is dependent on the rock conditions. Using more bolts than required introduce over-work (or over-processing, which is a waste), while using too few bolts will introduce re-work (another waste). By establishing a standard, based on worse rock conditions, the number and location of the bolts can be standardised. If the rock conditions are better than the standard assumes, this could result in extra costs the in form of additional material used, more work hours required etc. However, the process time *variation* will be reduced, which, in turn, will allow for a standard time to be established, which is needed for the production process to be balanced.

Furthermore, the authors also bring up the dimension of quality: without standardisation, the quality of the work has to be inspected visually by the operator (which relies on the operator's judgement and knowledge). Incorrect quality control may introduce rework as well as the potential for failure (e.g. in the case of rock bolting). Standardised work will reduce the need for quality *control* and will shift the focus to quality *assurance*.

For the implementation of TPM, the authors bring up the long distances between the mine face and the maintenance areas, and state that, already, operators are encouraged to do simple non-routine maintenance. However, they are also quick to note that this approach has downsides as well: on one hand, it could reduce the downtime as the "waiting time [for the] maintainer is eliminated" (p. 7); but, on the other hand, if the operator does not have sufficient skill and knowledge of maintenance, it might increase downtime as rework would be required and/or the frequency of failures would increase.

For QCO, the authors maintain that it mostly relates to maintenance[13]. Their focus seems not to be so much on the operating phase, as it is on the design phase, arguing that QCO deals with the maintainability of the equipment and the ease with which it is maintained. Attention should be given to the design phase to design for maintenance and completely "design out" maintenance where possible. For this, "intense communication and cooperation between [the] end user and [the] equipment developer is encouraged" (p. 7).

On the topic of 5S and "Visual Factory" (i.e. visual control), the authors note that the visual factory and the use of 5S is a normal starting point for companies start their "Lean journey." They also bring up the fact that mining companies often employ a substantial amount of contractors which might be potential hindrance in applying LP. The authors argue that a contractor may not share the same values as the contracting company and might refuse

[13] Considering maintenance as setup time might not be immediately obvious or readily accepted, but if maintenance time is viewed as a time required before production can begin, it is possible to follow the argument conveyed by the authors.

to partake in efforts such as 5S and visual factory, simply because it is not a part of the contract.

JIT and "Respect for people" are only discussed briefly in the paper. JIT is considered the weakest part in applying LP in mining because of remote locations and the tendency for large batch operations. Regarding "Respect for people", the need for empowerment and up-skilling through structural training is mentioned, but a challenge in this, the authors argue, is the high labour turnover that exists within the mining industry, which has turned efforts to training new workers.

Hattingh & Keys

This paper, *How applicable is industrial engineering in mining*, is from a conference proceeding. It was written by Hattingh & Keys and published in 2010. It does not focus solely on LP but rather on the applicability of industrial engineering in mining, in which LP is included. No specific tools or principles are brought up for discussion in the paper, but the need for standardised work is covered:

> Standardization is the foundation that enables organizations to change and improve their processes. In an environment where the methods and plans used to perform work constantly change from one worker to another, or one day or shift to another, high levels of variation are a certainty. This variation firstly makes it impossible to plan adequately and secondly makes it very difficult to identify the root causes of problems. In addition, if any attempt is made to improve a poor work method, it will be difficult to implement changes and link them to improved outputs. Once flexible standards are in place, effective problem solving can be implemented. (p. 205)

The paper ends with two approaches to general business improvement. Although the covered approaches do not focus on LP per se, the key features for enabling more sustained approaches to improvement and implementation are still applicable to LP and LM. These are said to be:

> Linking all initiatives to the overall purpose of the organization; A move to long-term sustainability and away from short-term, quick fix solutions; Involvement and support from a senior level; Following a structured process to identify root causes and solve problems; The use of industrial engineers as coaches and facilitators; Drawing on local knowledge and expertise to solve problems; Imparting knowledge gained and problem solving skills to all levels of the organization; Linking initiatives to performance measures; Involving employees in the setting of targets. (p. 209)

To conclude, the authors argue that structured problem solving needs to replace short term fire fighting and that engagement in process and its ownership has to involve everyone, otherwise mines will not improve operational efficiency.

Steinberg & De Tomi

This subsection is based on an article by Steinberg and De Tomi, published in 2010, with the title of *Lean mining: principles for modelling and improving processes of mineral value chains*. It is a theoretical study with a focus on the mineral value/supply chain at a high level.

Much of the paper relates to the implementation of the LP way of thinking and how an implementation could be performed. In describing how to implement the concept, the authors present a table with practices common to the mining industry together with the practices that should be reached with the help of LP (see Table 5).

The process of applying LP to the mineral value chain is prescribed to start in the restructuring of the logistics network. After mapping the processes of the value chain, all activities that do not add value to the product, from the customer's point of view, should be eliminated. Following this step, the logistics network is improved by applying advanced managerial models. Here, the authors note the importance of defining value and the challenges of doing so correctly:

> The ability to understand and manage the relationship between value and end customer needs is one of the major difficulties to implement the lean thinking methodology in mining. The conventional operating mode of the mining industry is to push high production regardless of demand and to store products as ready-to-go 'commodities' at the ending nodes of the logistics channels. … For a successful lean thinking implementation, the management challenge is to provide appropriate fluidity to the value-adding processes and activities. (p. 292)

It is further argued that LM would provide companies with the ability to meet the requirements of the end customer almost instantaneously and with efficient logistic solutions.

The authors also state the importance of proactive participation throughout the entire company and production process: all participants – operators, manufacturers, distributors, and so on – should have a thorough knowledge of the production process and should continuously seek better ways of creating value. It is also noted that

> … the improvement process should be implemented in such a way that it is incorporated in future events such as the design of new facilities, fleets and routes, or even in design of supply and distribution channels within mining companies. (p. 288)

The discussion then move over to Six Sigma (which is also mentioned in Table 5) and how it can be used to overcome the challenge of managing discrepancy between planned or estimated outcomes and the mining operation results. The discussion returns to LM in stating that success in achieving drastic change "requires a strong commitment towards educating and training the staff involved in the mining process" (p. 294).

Table 5: Lean thinking transforming old practices (Steinberg & De Tomi, 2010).

From	To
Compliance	*Commitment*
Exclusive focus on efficiency. Posture: "I can live with that". Changes are not needed	Commitment and engagement with the process of cultural change
Complexity	*Simplicity*
Guidance for perpetuating complex processes and accepting losses in the value chain	An orientation for processes whose success is measured by its speed and simplicity
Tolerance with the error	*Elimination of error*
Acceptance of a certain margin of error and a consequent undisciplined corrective actions taking	Six Sigma is a constant goal in everything that is done. Guidance to raise the Sigma level of processes
Weak measures	*Strong measures*
Financial measures incomplete or ambiguous; without inspection process of the impact on business results	Financial measures solid, documented and aligned with the results of the business; formal monitoring system for the projects development
Analysis	*Collaboration*
Departmentalisation of operations. Passive resistance to changes and virtual impossibility of success in multidisciplinary projects	A collaborative mentality, and an informal standard pattern of discussion and debate of multidisciplinary project
Impatience	*Discipline*
Urgency style. Attack the less important and short-duration benefits. Declaration of premature victory over results	Focus on the long term and sustainability of the results. Discipline in the method

Sanda et al.

This grouping is represented by the conference paper *Miners' Tacit Knowledge: A Unique Resource for Developing Human-oriented Lean Mining Cul-*

ture in Deep Mines by Sanda et al., published in 2011. It is based on historical data, data from observations, and interviews from a mine in northern Sweden. The study is focused on the creation of a human-oriented LM culture in which "Human Added Value" is an important aspect. To illustrate Human Added Value, the authors give the following examples:

> The miners' use … tacit knowledge to successfully negotiate task involving hard rock, and as a consequence increase the pace of their work activities … The capture and modeling of this Human Added Value as a culture attribute of lean mining is important because organizations are social structures entailing sociocultural constraints that could hinder the prospects of employees playing a decisive role in improving its performance. (p. 403)

The paper puts much weight on the importance of workplace cultures; how culture can both help and hinder the process of realising LM. The authors argue that benefits could be derived from the mine workers by involving them in a workplace transformation towards leaner mining. Such an involvement would also provide the workers with a good platform for sharing their tacit and explicit knowledge (e.g. about work processes or the "rock").

The paper concludes by stating that the knowledge-derived human-added value that is held by individual miners could be extracted and be used as an addition to the two priority tasks[14] for achieving LM. That is, a platform should be created to capture the tactic knowledge of the miner and integrate that knowledge in the design and development of a LP culture.

Ade & Deshpande

This article has the title *Lean Manufacturing And Productivity Improvement In Coal Mining*, published in 2012 and written by Ade and Deshpande. It is included here to nuance the picture of LP and its application in mining.

[14] These are the priority tasks presented by Haugen, below.

The paper describes use of the LP methodology to identify possibilities to improve the performance of the drill bits utilised in an Indian coal mine. The solution includes the redesign of the tool bit profile and training, in accordance with the PDCA cycle. Instead of being an illustration of the possible application of LP to a mining environment, it seems some methodologies or philosophies of LP are used to justify the improvement of, in this case, tools.

Helman

The article, *Analysis of the potentials of adapting elements of lean methodology to the unstable conditions in the mining industry*, is written by Helman and was published in 2012. It is a conceptual study of the possibility of adapting the principles of LP to the mining industry. Much effort is spent on comparing the conditions of the mining industry to the conditions of the automotive industry, and how that would affect the implementation of the elements and tools of LP. This is summarised in Table 6.

The analysis of the adaption capability of the different tools and methods of LP is then covered. The following tools and methods are included in the analysis: JIT, One Piece Flow, TPM, 5S, *Kanban*, *Heijunka*, and Continuous Improvements.

JIT is argued to be possible to implement in the process of having parts supplied from vendors, and in warehouses at the mine site. One Piece Flow, on the other hand, cannot be implemented directly, as the One Piece Flow requires a discrete process and mining being more or less continuous.

TPM is said to be possible to use "as is" to improve the time between failures of machines. 5S also represents a tool that would require little to no modification; the practice could be adapted in any workplace or storage where tools and machinery is present.

Table 6: Comparison of specificity of the mining and the automotive industry (Helman, 2012).

Mining industry	Automotive industry
Work of customers cannot be stopped, thus production at the mine is the push system	The assembly line can be stopped, so transformation to pull system is possible
Continuous production	Production in cycles
Unstable/variable operating conditions	Stable operating conditions
Variable work environment	Permanent work environment
Geological hazards can halt the production	No threats to production
High volatility of the availability of materials	Controlled availability of materials
Large dispersion of work (up to several km)	Working in relatively small factory
Customer mine are other industrial companies	Sales of products primarily individual customers

The utilisation of *Kanban* would be challenging in the production process itself. This is attributed, by the author, to the nature of the transportation systems used in mining. Like JIT, *Kanban* is proposed to be applied in warehouses for part ordering, and for the control and planning of unloading places and storage. For *Heijunka* it is stated that it could be applied for all the same areas that are applicable to *Kanban*. Finally, continuous improvements seem to involve no challenges in its application to mining. The tools, their adaption potential and possible implementation is summarised in Table 7.

The topics of competence and implementation are also covered. For competence, cross-training is recommended for the increase of qualifications of the miners. Tutors are suggested to be persons with extensive experience in, for example, operating a certain machine, or foremen. As for implementation, it is concluded that the first step should be the analysis of mining, manufacturing and business processes, where the aim should be to adopt existing LP methods and tools to the needs of the mining industry.

Table 7: Summary of adaptation analysis (adapted from Helman, 2012).

Method/tool	Potential to adapt?	Possible implementation
JIT	Yes	Ordering system and all warehouses
One Piece Flow	Not directly	Flow diagram of the machines and operators, cross-training
TPM	Yes	All vehicles and conveyors
5S	Yes	Storage, tool chamber and other rooms where equipment or material is present
Kanban	Yes	Warehouses at heavy machinery chambers, machines, shaft bottom
Heijunka	Yes	All places covered by Kanban, shafts
Continuous improvements	Yes	For miners, foremen

Shukla & Trivedi

The paper, *Productivity improvement in coal mining industry by using lean manufacturing*, by Shukla & Trivedi was published in 2012. It adds little to the topic of LM. However, it is worth mentioning as the authors' view on the tool is somewhat different from other authors. They view it as a tool for improving the well-being of the mine workers; calculating the time and energy lost in not providing the mine workers with motorised or mechanised transportation to the mine front, they argue that such transportation should indeed be provided. It seems the concept is used to justify an improvement, rather than using the methodology of the concept itself to improve the situation.

Haugen

This grouping represents one report, one section from another report and one article, all written by Haugen: *Mine of the Future (MIFU) – Work Package 4: Lean mining* (published in 2010); section 4.4 (*Leaner mining*) in the report *MIFU – Smart Mine of the Future* (published in 2010); and *Lean mining* (published in 2013; this is the article that will be referred to in this section), respectively. These texts probably represent one of the more ambitious efforts in the subject of LM. Using Liker's 14 principles, Haugen discusses the potential of adapting TPS to mining. The most important conclusions and points of discussion have been summarised in this subsection.

In times of low ore prices, the mining industry is prone to production increases (rationalisations) and "headcount reductions" which would go against the principle of long-term philosophy, states the author. The long planning horizons and expensive equipment (requiring long payback times) would, however, fit in well with the philosophies of TPS. On the other hand, the ownerships of mining companies are often fragmented, which could disadvantageous.

Concerning the establishing of a continuous production process, Haugen states that mining operations are exposed to variations in ore grades and rock conditions as well as fairly poor availability of the production equipment (e.g. the mean time between failures for many machines is less than 30 hours). Variable operating times, machine failures and other disturbances contribute to the uncertainty. As a result of the unpredictable nature of the mining operations, large buffers stocks, or work in progress, are used to protect the production while the disturbances remain. Under these circumstances it is very difficult to create a continuous flow.

For customer demand production, the author observes that mine production is planned based on availability of production areas in the mine; a historical achieved capacity from each mining area is combined with a desired capacity increase. The daily scheduling and release of work is traditionally left to the individual supervisor's discretion. Conflicting priorities that Haugen note are beliefs that expensive machines (or those in the beginning of the mining cycle) should be manned at all times, and that work must be assigned to them, even though other activities in the mining cycle cannot keep up. Due to the large distances in the mine, it is assumed that so much time is lost when operators change from one machine to another that this should be avoided. Furthermore, the author notes that there are more machines than operators in the production system; what machines that are manned are occasionally influenced by the competences and preferences of the workers that have reported to work. In cases where the mill is a bottleneck, it might be decided to keep a large inventory of ore before the mill to allow for stops, weekends etc.

When it comes to variations in workload in multi-front mining operations, with blasting at fixed intervals, Haugen describes "waves" of activities moving through the system. Right after blasting there are many headings waiting for loading; later, the demand is for scaling; then, for shotcreting; and so forth. Having certain activities, like shotcreting, available only on dayshifts introduces the same fluctuations in workload. If ore production is lagging behind the plan, ore transports are prioritised at the expense of waste rock, and certain services and installation of rock support may be postponed until later. In operations with both small scale and large scale mining methods, production in the small scale areas is slowed down if there is good availability of large scale stopes, thus creating large fluctuations in workload. Fluctuation, in turn, prevents stability which is said to be required for LP.

According to Haugen, product quality is not a major concern to most base metal producers, but internal quality problems result in rework or affect the future production system negatively (e.g. uneven ramps or unstable pillars). As in traditional western mass production, the mining industry strives to keep production rolling at all costs. Rather than eliminating the root cause of problems, it is accepted as an unfortunate but unavoidable nuisance. A prevailing attitude is that loss of production is too costly to risk revealing problems that might not be easily solved. Bringing problems to the surface some-time has a negative association attached to it: it is seen as complaining or blaming people for mistakes. Instead, it is preferred to talk about and learning from successes rather than failures. Another aspect of this issue is the belief that the mining process is so unpredictable that solving yesterday's problems has no impact on tomorrow's situation, when a completely new set of problems will surface.

Concerning standardisation, Haugen finds that, during the last 10-20 years, the mining industry has removed itself from detailed, written standards or instructions. Standards were perceived as preventing initiative and improvement. By training operators properly, they would themselves be able to select the proper cause of action in each individual situation. This change may be motivated by the prevailing perception that conditions in mining vary considerably and that this prevents the establishing of one best way of performing operations.

Multifunctional teams with some responsibility for maintenance do exist in the mining industry, according to the author. Operators are multi-skilled, sometimes to the extent that it is not possible to trace which operator performed a certain task at a given time. The operators may rotate to get variation and reduce stress, and at times an operator may not know what activities he or she will be performing before the beginning of the shift. In development and tunnelling, small teams with a supporting team leader may be found. Previously, mines were split into production levels with small, three to four man teams with dedicated production equipment being assigned to them. This team was responsible for all production activities on that level, including maintenance.

To conclude, the author provides two recommendations for research and development to help overcome the obstacles standing in the way of LM: (1) improving the reliability of the mining equipment, and (2) creating a continuous mining process, with the uncertainty of ore grades and rock quality being addressed in subsequent steps.

Liu

Study on Coal Lean Mining Theory and Practice is by Liu and was published in 2013. While it presents a structure for LP (and its implementation), the author does not necessarily adhere to it. The implementation consists of the researcher identifying waste in a process and presents ways to reduce this waste. The author observes the activities a group with the task of setting up support pillars. After identifying different kinds of waste, the author comes up with ways of reducing the waste. This ends up reducing the total process time by 77 minutes which represents an improvement of about 17%.

However, it should be noted that safety is also being considered. The author mentions that LP should improve "workers' productivity and ensure lower the workers' fatigue level without labor intensity rising [sic]" (p. 539). Furthermore, the author states one of the objectives of LP as being improving the working environment and that "[i]t should improve the harsh environment of mining face, and provide workers with relatively safe and comfortable environment [sic]" (p. 539).

Another interesting thing to note is that the author provides a basis for the implementation, even if it is somewhat primitive. It is stated that "[t]o guarantee the implementation of the scheme[15], advanced production technology, good interpersonal collaboration and advanced computers and technology of information are needed" (p. 539). The article also mentions the importance of the LP philosophy being adapted by the whole company.

Castillo et al.

This grouping is represented by the 2014 article *Implementing Lean Production in Copper Mining Development Projects: Case Study* by Castillo et al. The article is the result of three case studies on LP implementation attempts in development projects at mine sites. The article represents somewhat of an anomaly:

[15] "the scheme" presumably refers to the concept, i.e. Lean Production.

instead of looking to the classic Lean *Production* version of the concept, the authors instead look to Lean *Construction* (it will still be referred to as LP in this section, however). The authors argue that this is justified as the development works in mining is closer to construction than it is mining, stating that "[m]ining development projects in copper mines are currently undertaken by construction companies and involve mostly tunneling and other construction operations that are required to prepare the mine for exploitation" (p. 1).

Castillo et al. identified the need to improve planning and coordination, communication between parties (including managing knowledge and using process information), and alignment of parties, as well as to reduce operational waste, and consolidate work teams. The LP implementation was defined by five components: communication plan; improvement of planning and coordination; structuring of operational coordination; continuous on-site improvement; and process optimization. The LP implementation itself consisted of several tools and methods: identification and reduction of waste; delay surveys; Last Planner System; phase scheduling; value stream mapping; implementation of 5S; visual control; and continuous improvement.

The impact on production performance following the implementation of LP was measured in interferences, physical progress, plan reliability, productivity, and time efficiency. The authors report that positive improvements for all indicators in all three case studies: "[i]t can be concluded that there was a trend toward improved performance in the production indicators when comparing data distribution before and after lean implementation" (p. 7).

The impact on organisational performance was also measured. This was done using a survey and interviews, utilising measures for teamwork, participation, communication, commitment, and learning, for the survey; and enterprise vision, technical competencies, and social competencies, for the interviews. The impact recorded from the survey showed a positive influence on all variables. Regarding the interviews, the results were more varied, with the greatest impact being on enterprise vision. The authors state that "lean implementation had a positive impact on the performance of the organizations, according to the perception of both the team that developed the implementation and the teams that were analysed in the case studies" (p. 9).

Apart from the actual implementation and the subsequent results, contractors are also covered, in that the improvement program was introduced because of the mining company's problems with contractors (mainly low productivity).

Maier et al.

This grouping is represented by a paper in a conference proceeding in 2014. Its title is *Adopting lean and characteristic line based industrial methods for optimizing room and pillar processes* and is written by Maier et al. It is unique in this review in that it attempts to establish "a model for transformation of planning objects and objectives as well as the KPIs (Key Performance Indicators) between industrial processes and mining processes" (p. 2). To do so, the room-and-pillar mining method is examined. The focus is on medium-term planning and operations relating to "loosening actions", i.e. the breaking or fragmentation of rock.

The authors "match" the different aspect of LP to mining. In the case of the interaction between production resources and the products, it is noted that, in mining, the product itself is fixed and the production resources (such as vehicles and machines) are moved, while in manufacturing it would be the other way around. They, furthermore, note that, while the production sequence in manufacturing is often visualised as being sequential (or "flowing"), it would be visualised as cyclic in mining. They, thus, conclude that the face is equal to a semi-manufactured product (i.e. work in process, WIP). The "matching" of the inventory then follows: if prepared faces are to be considered WIP, the amount of these faces would be the inventory.

For the matching of variants, it is noted that, since the sequence of operations in mining is always similar (the authors argue that differences in the production sequence constitutes as variant), there is only one product family in mining in the “traditional” sense. What would essentially constitute a product family in mining would then have to be based on location. This is because the most obvious, changing process property is the face location; the location of the face determines its properties, such as voids and moisture. In theory, each face would be its own product variant, but, to simplify, the authors treat all faces covered by one tipping point as one variant.

The above “matching” is concluded by the comparison of the KPI of mining and manufacturing. It is presented in Table 8.

Table 8: Comparison of KPI's based on the VSM (Maier et al., 2014).

Mining	Manufacturing
Working time	Working time
Bulk	Process amount
Mineral content	Good part success chance
Technical availability	Technical availability
Maintenance	Maintenance
Driving times	Changeover times
No. of faces per tipping point	Lot size
Number of prepared faces	Inventory

SOME COMMENTS AND REFLECTIONS

The reviewed texts merit some further comments and reflections. The below text will first and foremost be based on the questions posed in the introductory section of this report. Note that the headings do not directly correspond to the questions as the “answers” usually overlapped. As such, covering several questions under one heading represents the easier way of presentation.

Other topics of interested were also discovered during the review. Generally, the discussion surrounding these topics are not as fleshed out as the other topics in this section, but their inclusion in this report should still be considered justified

What has been done to date?

While the literature on LP is clear on the need to introduce the concept of LP "as a whole" to the entire organisation (e.g. Liker, 2004; Womack & Jones, 2003), and some authors in the reviewed text also advocate this approach (e.g. Dunstan et al., 2006; Yingling et al., 2000), this is not always a practical possibility. This is seen throughout all the case studies and practical examples where no case included a "complete" implementation. Even the conceptual studies provide a similar picture: some of the LP practices are not suitable for all mining operations and activities.

Focusing, then, on what *has* been done and beginning with the case studies, three areas where LP implementation efforts have been focused can be identified: service bays/machine shops (Dunstan et al., 2006); developmental works (Castillo et al., 2014; Dunstan et al., 2006); and mine-face work (Klippel et al., 2008a; 2008b). It should be noted, however, that this excludes areas such as smelters as covered by Dunstan et al. (2006). It is especially service bays/machine shops and developmental works that are of interest. This is because they are the areas also noted in many of the conceptual studies. The supporting functions (e.g. the service bays/machine shops) are considered suitable for implementation as they are not constrained by the same limitations, as the main functions of mining activities might be; it could be argued that these supporting functions are more like activities where LP is usually successfully implemented.

A case, similar to that of above, can be made for development works (e.g. Castillo et al., 2014; Haugen, 2013; 2010). Here the same constrains as might apply to mine exploitation may be avoided, i.e. blasting does not have to take place at designated times, and, at times, the drill and blast method is also possible to forgo in favour of shearing techniques for rock fragmentation (e.g. using roadheaders).

To summarise, when it comes to actual implementation, supporting functions and developmental works seem to represent the areas with most "implementation potential". Support for this is found in most theoretical studies as well, although they are usually more positive regarding what areas are possible for implementation. Furthermore, most theoretical studies make the case that actual "face work" is among the less suitable implementation areas, with high variations in working environment and "product" quality (ore grade) being cited as a reason. There is some evidence that LP is possible to implement at the face (Klippel et al., 2008a; 2008b), though. In this case, only small part of the concept was implemented, however.

Suitable tools and practices

As for what practices and principles of LP that is considered for implementation, there is a considerable difference between the case and conceptual studies. The conceptual studies are more positive about the adaptation possibility of the different practices and principles to mining, while the cases studies are a bit more moderate[16].

The case studies seem mostly focused on the practices related to the principle of waste elimination. Having such a focus does make sense as many of the practices are not limited by the mining environment (e.g. 5S, visual control, and standard operations), or is to some extent already practiced, as in the case of TPM (Wijaya et al., 2009; Yingling et al., 2000). Practices such as these are also a common starting point for companies implementing LP (Wijaya et al., 2009), which could help explain their frequent appearance in the litera-

[16] This is not to say that some of the authors of the case studies do not believe the concept could be applied to all mining activities, but their recorded attempts usually focus on one or a few LP practices.

ture. As such, their frequent mention in the texts should not necessarily be taken as proof of their "greater applicability" as compared to other principles.

The conceptual studies, meanwhile, to greater extent argue for the potential of adaption of most of the LP practices; a majority of the practices are described to have a certain possibility of implementation. However, practices related to the principle of aligning production to demand, represent a more complicated set of practices that would be more difficult to implement in a mining environment. They are, however, by several authors, considered possible to implement in supporting functions.

Both the principle of involving the workforce and that of supplier integration are covered, but to a lesser extent. None of these principles, though, should represent any greater complication in their application to mining. More than anything else, involving the workforce is an organisational measure; in a simplified manner, the suggestions of the workforce just have to be heard and considered. Some concerns might be voiced in this, though. Mainly it would be in regards to the size of the mines. Where, in a factory, the ability to gather the workforce for *kaizen*-meetings is greater and easier, in a mine, the several kilometres that have to be traversed to reach one's place of work, is said to considerably inhibit this ability. However, the concept is still achievable as *kaizen*-meeting, or similar, can be held at shift changes, for example.

The integration of suppliers is also mainly an organisational consideration. It is also a concept that applies to higher levels of the value chain. It would be about building stable and mutually beneficial partnerships with the mining company's different suppliers. As such, the application of this principle is removed from the mining environment. Considerations that are more relatable to mining are those of contractor utilisation. If they are considered suppliers, what may be an issue to solve is the number of contractors employed by some mining companies. Is it, for example, possible to develop the required partnerships with so many partners?

Attempted implementations and results

The case studies are few in number and as such it is hard to comment on the effects of LP in mining in anything more but in a brief manner. No negative results have been reported, although some occurrences of neutral ones can be identified (e.g. Castillo et al., 2014; Dunstan et al., 2006).

Among the recorded effects are increased productivity (e.g. increase in mined tonnage per miner or length of tunnelling developed per day), improved health and safety (e.g. fewer accidents or less air pollutants at the mine face), and improved communication. It is important to note, as is highlighted by Castillo et al. (2014), that these are all short-term effects. It is a frequently expressed concern that immediate effects are often observed following initial work with LP, the problem, however, is maintaining these positive effects (Liker, 2004).

Because of the situation being as described above, effects are hard to comment on. The theoretical studies mention some effects that could be expected, but these are general in nature and are not different from effects promised by the management literature on LP. Instead, it might be more practical to look at *how* the implementation took place. This is important, especially for practitioners. However, information regarding this is also spare in the reviewed texts. There are essentially two “helping” factors brought up throughout the texts: previous experience with similar concepts and management’s involvement. The first factor is brought up by Dunstan et al. (2006), while the second is mentioned by most of the texts (both case and conceptual studies). As such, it seems important factors for a successful implementation of LP in the mining sector do not differ from factors important to other sectors. However, because this topic is never fully expanded upon in the texts, it is not possible to comment to what extent this statement might be true.

What is required to realise the vision of Lean Mining?

The opinions of whether certain developments within the mining industry are required to fully realise LM differ between the different authors. To simplify the issue, it can be said to be about the attainment of one out of two goals: the first, the utilisation of the LP practices as a tool to attain, for example, one-piece flow; the second, to apply the underlying philosophy of LP to the organisation.

The first goal would, to a greater extent, be dependent on variations in mining cycle decreasing. Throughout the texts, different solutions for this are proposed. The standardisation of operating procedures is one such solution (Wijaya et al., 2009), but it does not solve the problem with variation in ore grade, however. Haugen (2013), on the other hand, suggests the development and utilisation of continuous miners in metal mining. While this does not necessarily solve the problem of variations of ore grades, it would be less dependent on prepared faces and planning, therefore being able to compensate low ore grades with additional mining. In addition, if the concept of multi-functional continuous miner (i.e. one that has the ability to both mine and reinforce the drifts, for example) was to be realised, even less planning may be required. A multi-functional continuous miner would also be a step on the road to LM, in that it partly aligns with practice of having non-dedicated production equipment.

The other goal – i.e. the goal of applying the Lean *philosophy* to mining – is less dependent on the development of specific technology. Instead, the focus here should lie on aligning the organisation's culture and values with those of the Lean philosophy. This is highlighted in several of the reviewed texts. The issue in this goal is also noted, albeit by a fewer number of authors: is it possible to attain and sustain a Lean culture in a sector with high labour turnover – as described by Dunstan et al. (2006) and Wijaya et al. (2009) – and/or with a high reliance on contractors (Wijaya et al., 2009)?

In the case of contractors, although not brought up by the texts, a possible way forward would be to adopt Lean's practice of supplier development activities (as briefly discussed above). The mining company could challenge contractors to and help them adopt a Lean way of working, rewarding those successful with long-term contracts. As for high labour turnover, the solution most likely lies in providing more attractive workplaces – something that, on one hand, might be accomplished with the help of a Lean company philosophy, but, on the other hand, might have to be achieved to be able to adapt a Lean philosophy in the first place. In this, Yingling et al. (2000) makes a case for providing employees with permanent job security.

Mining's unique characteristics and their effect on implementation efforts

There is no doubt that differences exist between the mining industry and the "traditional" LP industries (e.g. the automotive industry). While these differences might seem significant, they are reduced when comparing to "untraditional" industries that have successfully adapted the LP concept. Mining production is continuous, as opposed to cyclic, as in the automotive industry – but so is the process industry, and it has seen successful implementation attempts (e.g. Lyons et al., 2013); nature hazards can halt the production, where the automotive industry have very few external threats to the production – but so does the construction industry, and it has seen successful implementation attempts (e.g. http://www.leanconstruction.org/ and http://www.iglc.net); and so on.

It is, of course, important to be aware of these differences and the barriers they might represent, but it also important to realise that too great a focus on these issues might take away energy that might otherwise have been spent on adapting the concept. To clarify: the work with adapting the concept has to start at some point; if it is continuously put off, in waiting for solutions to the issues the differences between industries might bring, the effort might ebb away.

Other topics of interest

The topics covered in this subsection were not considered by the initial research questions. Most of the topics below are based on themes that have frequently reoccurred in the reviewed texts. The comments and reflections regarding these topics will not be as detailed as the previous ones of this section. These topics might also be suitable for further investigation and study, and should, preferably, be properly answered to help in realising LM.

Lean and stable production processes

As argued by Haugen (2013), the variations and instability of the mining process would have to be improved considerably before LP can be fully realised in the mining industry. The conclusion drawn from this is that the realisation of continuous miners – a move away from the traditional drill and blast way of rock fragmenting – and improved machine reliability has to be awaited before a full adaption can take place. This, however, is in conflict with Yingling et al. (2000), who state that "stability is achieved through practices such as standardised work, quality at the source, and total productive maintenance" (p. 223). From this, it follows that the full adaptation of the concept is not necessarily dependent on the development of technology. It could, in fact, be argued that TPM is the way of improving machine reliability and, thus, also production stability. This is not to say that continuous miners are not desirable – they very much are. The case to be made here is that LM can be approached even without these technological advances.

What constitutes Lean Production?

Several of the papers bring to light an issue regarding LP that is not limited to the mining industry. It is on the question on what might be called LP and what LP indeed is. Klippel et al. (2008a; 2008b), for example, focus on eliminating waste. Even though the method of process mapping might be a relatively new, the drive for eliminating waste has been on the agenda since a long time back. The issue also rears its head in the motivation behind the implementation attempt. Looking again toward the papers by Klippel et al.

(2008a; 2008b), we see a clear focus on the reduced costs in the results, this all the while Yingling et al. (2000) argue that LP is not about cost cutting.

What is important, and arguably more so than the discussion of whether or not a certain intervention might be considered LP or not, is the underlying goal of the rationalisation intervention. These goals will undoubtedly steer improvement efforts. Authors, such as Liker (2004) and Womack and Jones (2003), often highlight win-win character of the concept, i.e. both the employee and company comes up as winners, following a successful implementation. However, if the goals are purely monetary in character, the working environment of the employees might only be considered if it also improves productivity, for example. This can be seen by, once again, looking to by Klippel et al. (2008a; 2008b). The improvement that resulted in better working conditions was motivated by reducing waste in the process. The fact that dust concentrations dropped was mostly a side-effect.

The point trying to be made is the following: whether or not a rationalisation effort is called "Lean" or not is unimportant; what is important is that the goals are stated such that the working conditions of the employee improves as an effect on the rationalisation.

Operator influence over quality

The operator's control over what can be considered product quality is mentioned by some of the authors (e.g. 2013; Haugen, 2010; Yingling et al., 2000). The consensus seem to be that product quality is hard to control, being in a high degree decided by ore body and rock characteristics. As mentioned above, uncertainties might be reduced with the help of new technologies, but no sure-fire way of controlling product quality is provided. Instead, like other practices of LP, its application is considered for supporting functions – in this case, quality is talked about as a way for ensuring safety. It is argued that LP's focus on quality could be used to guarantee the stability and safety of the working face before work is actually started, i.e. operators are themselves responsible for their work having been correctly performed and is of a satisfactory quality, before it is "passed on" (c.f. quality-at-the-source).

Standardised operations are also mentioned in this context and, amongst the texts, there is an interesting conflict of opinions. While most authors discuss seem to be in favour of the concept, there are two opinions that are close to direct opposites of each other: Haugen (2013; 2010) who argues that standards and instructions are perceived as inhibiting for initiative and improvement, in part because conditions in mining vary considerably; while Hattingh & Keys (2010) argue that standardisation is the foundation for change and improvements, since if methods and plans constantly change, a high level of variation is a certainty. It can, of course, be argued that the disagreement lies in the definition of a standard. If a standard was to be defined as rigid and inflexible descriptions of how work is to be performed, pessimism about the practice's applicability to mining might be more easily justified. In fact, the argument conveyed by Hattingh & Keys (2010) is for *flexible* standards. It follows that the standards have to be fit for purpose; standards as prescribed to the more stable environment of the automotive industry has to be carefully adapted to suit the more variable mining environment. As there is some evidence from the case studies that the introduction of standards can have at least short-term positive effects, a case can be made for introducing flexible standards to mining.

Multi-skilled operators

A reoccurring theme in the conceptual studies is that of multi-skilling and multi-functional teams. The training of employees to be multi-skilled should incur no more difficulties than any other industry utilising the LP concept. Despite the strong promotion of the notion, it does not seem to be a part of the implementation efforts of the case studies. The exception is the case reported on by Klippel et al. (2008a; 2008b), who provide one practical example of multifunctional teams. In this case, the miners were organised in teams of three, with two operators performing the main activities and the third assisting in the supporting activities. However, it is important to note that the operators making up these teams are not described to have received any additional training. Furthermore, the goal was not to organise the work in teams, but it rather seems that this was a solution that provided the most efficient solution to the given problem.

"Pushed" production and high inventories – implications for Lean Mining

The mining industry has a tendency to keep high inventories and to "push" production, from the mining face to the enrichment plant (Steinberg & De Tomi, 2010). This tendency is also found in traditional western manufacturing (Haugen, 2013; 2010), but its practice in the mining industry might be further explained by how metals are traded; metals differ in that they are mostly sold to exchanges instead of directly to customers, and this, in turn, makes it possible for metals to always be sold. The demand for metal ore will, of course, affect prices. However, since metal ore has unlimited "shelf life", ore can just be stored at the end of logistic nodes (Steinberg & De Tomi, 2010), for example.

The philosophy of LP advocates low inventories and "pulled" production (i.e. the production responds to customer demand). With this and the above fact in mind, the question arises as to whether or not low inventories and pulled production is desirable for the mining industry. One might argue that it would not matter, as in prolonged periods of low ore prices, even the leanest mining company is in danger of perishing. Yingling et al. (2000), on the other hand, argue that the drive should be to make sure the business is profitable regardless of ore prices; low inventories and pulled production would be a part in achieving this, because less capital will be held up in work in progress, for example.

The ideas of low inventories and pulled production are not only about profitability, though. Liker (2004) makes a case for the principle to be adhered to, to "bring problems to the surface". This is not specifically to mining, but something which any business would stand to benefit from.

THE ROAD TO LEAN MINING

What remains, then, is to provide a map for a possible route forward. Based on the reviewed texts it is not possible to draw up a complete map of the road ahead, but some directions are available. This map will start with the definition of value and then follow the model provided by Lyons et al. (Lyons et al., 2013).

As most proponents of LP would insist, the first step in becoming "lean" is *correctly* defining value – correct, in that it should be value in the eyes of the customer. However, it is also argued that the definition of value should be extended to include all relevant stakeholders and their values and opinions (Wijaya et al., 2009). Does the definition of value, for example, take in consideration the values and opinions of relevant stakeholders (e.g. is the value defined in such a way that the societal value of low environmental impact is considered)?; or is the final customer's requirement that the work required to produce a certain product is done under fair conditions reflected in the values? Making this definition would be the first step on the road to LM, and all subsequent actions and decisions would have to be in line with this definition of value.

Waste elimination

With value defined, practices related to the principle of waste elimination should be adapted first. Starting in this principle makes sense as these practices are more general and are hindered to a lesser extent by the unique characteristics of mining, compared to other practices. Furthermore, practices such as visual control and 5S are included in the principle of waste elimination. This is advantageous in two respects: first, they are the first practices usually adopted by companies beginning their Lean journeys (Wijaya et al., 2009), providing some evidence of the practices' suitability as starting point; and, second, the effects of these practices are visual, which might serve as a motivator for the engagement of the workforce (Dunstan et al., 2006). These practices could be implemented in the whole of the mining operation (Dunstan et al., 2006) or, if options are more limited, in supporting function such as machine workshops and warehouses (Dunstan et al., 2006; Helman, 2012). Developmental works also represent a suitable area of implementation (Castillo et al., 2014).

Standards should be developed to allow for continuous improvements (Hattingh & Keys, 2010; Yingling et al., 2000). However, it is important that these standards are flexible (Yingling et al., 2000). This is a somewhat contradictory statement, though. As such, it might be better to talk about "action plans", an instruction on *what* should be done in a given situation but that does not specify *how*. Furthermore, it is important that these standards are developed with the involvement of the workers and operators themselves (Sanda et al., 2011). Without their involvement these standards might not just be rejected, but valuable information may also be lost. Even more so, the operators will have to be given proper training to be able to, themselves, identify areas of improvements and be aware of the effects of their proposed changes, e.g. how their working environment might be affected (Yingling et al., 2000). This is also something that could be introduced to the entire mining value chain; all employees of the company should receive training in the principles of LP (Dunstan et al., 2006; Steinberg & De Tomi, 2010).

Standards or "action plans" can be considered to be of greater importance in the actual production process, as this could decrease variations. Since the variation in the mining process represents a barrier to fully realising LM (or at least LP in mining) this could be considered a prioritised area. An example of standard operations in the production process would be the procedure of rock-bolting the roof; with the help of the operators, a technique (how many bolts, in what order, etc.) that guarantees safety, a good working environment, and efficiency can be found (Wijaya et al., 2009).

Continuing, TPM needs to be fully adopted to improve machine availability and, by doing so, also decrease variations in the production process (Bäckblom et al., 2010; 2013; Haugen, 2010). As there is some evidence of it already being practiced to a certain extent (Wijaya et al., 2009; Yingling et al., 2000), the implementation should be relatively "quick-fix" in nature. However, once again, it is of importance that the operators, who are doing this maintenance, get the training they need to successfully perform the maintenance. Otherwise, with faulty maintenance being performed, additional variation might be introduced to the production process, rather than reducing them (Wijaya et al., 2009). The practice of TPM would mainly apply to the activities related to the production processes, but could also be of relevance for supporting functions such as transportation.

Mistake proofing equipment is also of importance. When procuring new equipment, on-going communication with the manufacturer is required. The exact details of the mistake proofing (i.e. which mistakes are to be designed out) will, of course, vary for each machine. As examples, though, it is worth looking into the ability for machines to disallow too high loads (as this can introduce unnecessary wear to the machine), or speed limiters that prevent the operator from driving at a speed deemed unsafe. This would apply for most mining operations and activities.

Supplier integration

The principle of supplier integration can be of benefit to the mining industry. Apart from the "traditional" suppliers, contractors should also be included here. For the "traditional" suppliers, this principle does not differ much from any other industrial sector and should be implemented in the same way as in other sectors. Introducing the principle to contractors, however, should have a priority, as, not only are some mining companies dependant on contractors (Elgstrand & Vingård, 2013), contractors' working environment and accident rate is worse than those of regular employees (Blank et al., 1995; Muzaffar et al., 2013).

In applying the principle of supplier integration, contractor companies are to be challenged and assisted in their own journeys towards LP and their work in providing a good working environment. Those who are successful in this should be rewarded with long-term contracts. In this, when establishing supplier relationships, it is also important to look beyond monetary factors. Areas such as safety records should also carry heavy weight when choosing the most appropriate contractor.

As an alternative to this, the utilisation of contractors could be discouraged as a line in becoming more aligned with the philosophy of LP. Necessary knowledge and a sufficient workforce should be maintained, and this workforce developed and essentially offered permanent work security (Yingling et al., 2000).

Aligning production to customer demand

In providing a road map for leaner mining, the principle of aligning production with customer demand would constitute somewhat unknown or unmapped terrain. While the reader could, perhaps, be provided with some recommendations regarding this principle and its application to the production process, there is an almost unanimous agreement among the authors (who cover the issue) that the biggest potential for the principle today is in supporting functions. In its application in supporting mining functions, tools such as *kanban* should be applied to make sure supplies and material are delivered when needed, reducing inventories and creating a flow (Helman, 2012; Wijaya et al., 2009; Yingling et al., 2000). Furthermore, the arrivals of transports to the mine site should be uniform to help in keeping production levels balanced (Yingling et al., 2000).

It is clear that this principle does, indeed, represent the most "hard-to-realise" principle of the four covered in the model by Lyons et al. (2013). To actually arrive at mining that is entirely "Lean", with production directly responding to demand, further technological advances are required (e.g. techniques decreasing or at the very least controlling variations, and the development of continuous metal miners). In awaiting these developments, however, all that can be done in applying this principle should be attempted. And while focus might be rightfully prioritised to the other principles, this one should not be abandoned.

Workforce involvement

The final principle to be covered is that of the involvement of the workforce. This, too, is a principle that is not, to any larger extent, hindered by the mining industry's characteristics. For the most part, this principle, as described in the "Lean literature" (e.g. Liker, 2004; Womack & Jones, 2003), can be implemented as prescribed. There are, however, some exceptions that require some further clarification.

The idea of operators working in teams and being multi-/cross-skilled is not an idea that is new to mining; already there are instances where this is being practiced. It is, for example, not uncommon for one operator to be sufficiently skilled in several different machines (see e.g. Haugen, 2013; 2010). This should be practiced to an even larger extent, however; having operators able to operate all machines in the mining cycle will further increase both flexibility and stability. This also ties in with work being performed in teams. Although mining has, historically, to a certain extent, been performed in teams, this practice seems to have decreased following increased mechanisation. And the mechanisation might indeed make organising work itself in teams hard. Instead work tasks should be assigned to teams, who, themselves, *plan* the work in teams. In the future, as remote control will become more dominant, and work being performed with several operators in one control room, teamwork might once again be possible and work should be organised to foster this.

The issue of training has been brought up before in this section and the recommendation remains the same: operators have to be offered training (e.g. to become multi- and cross-skilled) and continuously have their competences developed. A solution also has to be reached regarding contractors. The goal of having multi- and cross-skilled operators might hindered by the involvement of contractors. If the reliance on contractors remains, developing their skills should be an integral part of the supplier integration principle.

Finally, shift changes should be used to disseminate information and involve the workforce in *kaizen*.

Concluding remarks

LP is a mind-set based management model and, as such, much of the work in realising LM will have to happen in the minds of employees and the employer. Values and philosophy will have to be aligned to those of LP. This, in itself, might constitute a significant part of the implementation efforts.

Following the realisation of the "soft" part of the concept, the principle of waste elimination seems most suitable for implementation. These practices and tools will have to be adapted and practiced throughout the company, and there is evidence of this being possible and advantageous. Also, integrating suppliers should beneficiary, especially if this solves the issue of contractors (either through integration or substitution). As the practice of supplier integration would differ little from other application areas of LP, it should be ready for implementation to mining. Demand-based production will have to be focused on supporting functions as a start. As work towards actualising continuous mechanical metal miners continues, the principle can start being implemented to the production process as well. And finally, the involvement of the workforce should encompass the entire implementation effort.

All in all, it seems that the mining industry is ready to at least being its journey towards LM. Even though some problems remain to be solved, they should not be considered severe enough to discourage starting LM efforts.

REFERENCES

Ade, M., & Deshpande, V. (2012). Lean manufacturing and productivity improvement in coal mining. *International Journal of Engineering Science and Technology, 4*(5), 2293-2299.

Bäckblom, G., Forssberg, E., Haugen, S., Johansson, J., Naartijärvi, T., & Öhlander, B. (2010). *Smart mine of the future: Conceptual study 2009–2010 final report*. Sweden: MIFU.

Blank, V. L. G., Andersson, R., Lindén, A., & Nilsson, B. (1995). Hidden accident rates and patterns in the swedish mining industry due to involvement of contractor workers. *Safety Science, 21*(1), 23-35. doi:http://dx.doi.org/10.1016/0925-7535(95)00004-6

Carayon, P., & Smith, M. J. (2000). Work organization and ergonomics. *Applied Ergonomics, 31*(6), 649-662.

Castillo, G., Alarcón, L., & González, V. (2014). Implementing lean production in copper mining development projects: Case study. *Journal of Construction Engineering and Management,* doi:http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000917

Conti, R., Angelis, J., Cooper, C., Faragher, B., & Gill, C. (2006). The effects of lean production on worker job stress. *International Journal of Operations & Production Management, 26*(9), 1013-1038.

Dunstan, K., Lavin, B., & Sanford, R. (2006). The application of lean manufacturing in a mining environment. *International Mine Management Conference,* Melbourne. pp. 145-154.

Elgstrand, K., & Vingård, E. (2013). *Occupational safety and health in mining - anthology on the situation in 16 mining countries* (Scientific report No. 47(2). Gothenburg: University of Gothenburg.

Hancock, S., & Sinclair, D. (2008). Meeting resource constraint demands in future mining to 2050. *First International Future Mining Conference,* Sydney.

Hasle, P. (2014). Lean production: An evaluation of the possibilities for an employee supportive lean practice. *Human Factors and Ergonomics in Manufacturing & Service Industries, 24*(1), 40-53.

Hasle, P., Bojesen, A., Per, L. J., & Bramming, P. (2012). Lean and the working environment: A review of the literature. *International Journal of Operations & Production Management, 32*(7), 829-849.

Hattingh, T., & Keys, O. (2010). How applicable is industrial engineering in mining. *The 4th International Platinum Conference,* Sun City. pp. 205-210.

Haugen, S. (2013). Lean mining. *Mineralproduksjon, 3*, B21-B40.

Haugen, S. (2010). *Mine of the future (MIFU) work package 4: Lean mining.* Gällivare: Nordic Rock Tech Centre.

Helman, J. (2012). Analysis of the potentials of adapting elements of lean methodology to the unstable conditions in the mining industry. *AGH Journal of Mining and Geoengineering, 36*, 151-157.

Johansson, J., & Abrahamsson, L. (2009). The good work – A swedish trade union vision in the shadow of lean production. *Applied Ergonomics, 40*(4), 775-780. doi:http://dx.doi.org/10.1016/j.apergo.2008.08.001

Klippel, A. F., Petter, C. O., & Antunes Jr., J. A. V. (2008a). Lean management implementation in mining industries. *Dyna, 75*(154), 81-89.

Klippel, A. F., Petter, C. O., & Antunes Jr., J. A. V. (2008b). Management innovation, a way for mining companies to survive in a globalized world. *Utilities Policy, 16*(4), 332-333. doi:http://dx.doi.org/10.1016/j.jup.2007.09.001

Liker, J. K. (2004). *The toyota way: 14 management principles from the world's greatest manufacturer.* New York: McGraw-Hill.

Liu, Z. (2013). Study on coal lean mining theory and practice. *Advanced Materials Research, 605-607*, 538-541.

Lyons, A. C., Vidamour, K., Jain, R., & Sutherland, M. (2013). Developing an understanding of lean thinking in process industries. *Production Planning & Control, 24*(6), 475-494.

Maier, M. S., Kuhlmann, T., & Thiele, J. C. (2014). Adopting lean and characteristic line based industrial methods for optimizing room and pillar processes. *Aachen 6th International Mining Symposia: High Performance Mining,* Aachen, Germany.

Muzaffar, S., Cummings, K., Hobbs, G., Allison, P., & Kreiss, K. (2013). Factors associated with fatal mining injuries among contractors and operators. *Journal of Occupational and Environmental Medicine, 55*(11)

Sanda, M. A., Johansson, J., & Johansson, B. (2011). Miners' tacit knowledge: A unique resource for developing human-oriented lean mining culture in deep mines. *Proceedings of the 2011 IEEE IEEM,* Singapore. pp. 399-404.

Shukla, R., & Trivedi, M. (2012). Productivity improvement in coal mining industry by using lean manufacturing. *International Journal of Emerging Trends in Engineering and Development, 6*(2), 580-587.

Steinberg, J., & De Tomi, G. (2010). Lean mining: Principles for modelling and improving processes of mineral value chains. *International Journal of Logistics Systems and Management, 6*(3), 279-298.

Westgaard, R. H., & Winkel, J. (2011). Occupational musculoskeletal and mental health: Significance of rationalization and opportunities to create sustainable production systems – A systematic review. *Applied Ergonomics, 42*(2), 261-296.

Wijaya, A. R., Kumar, R., & Kumar, U. (2009). Implementing lean principle into mining industry - issues and challenges. *18th International Synposium on Mine Planning and Equipment Selection,* Banff. pp. 1-9.

Womack, J. P., & Jones, D. T. (2003). *Lean thinking: Banish waste and create wealth in your corporation*. London: Free Press Business.

Yingling, J. C., Detty, R. B., & Sottile, J., Joseph. (2000). Lean manufacturing principles and their applicability to the mining industry. *Mineral Resources Engineering, 9*(2), 215-238. doi:10.1142/S0950609800000184