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RESOURCE-PRODUCTIVE OPERATIONS – HOW LEAN, GREEN AND CONSTRAINT MANAGEMENT APPROACHES BLEND TOGETHER

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Abstract: Industrial resource productivity is becoming a top management priority across manufacturing sectors. This is driven by trends on the supply side, (e.g. increasing scarcity of certain raw materials), as well as on the demand side (e.g. the surge in resource demand caused by the growing number of consumers). Resource-productive manufacturers aim to optimize variable costs for materials, energy, water while taking the operational requirements such as throughput and quality into account. This paper investigates how lean, green and constraint management approaches can be leveraged to help reduce waste and cost in manufacturing through the application of an integrated loss bridge.
Keywords: Resource-Productive Operations, Operations Management, Lean and Green, Theoretical Limit

1. INTRODUCTION

There are many reasons why resource-productive operations are important in today´s context: Climate change, resource constraints, a rising population, cost improvement pressure, need for growth, to name just a few. The "Limits of growth report" [1] already in 1972 came to the conclusion that natural resources are becoming scarce, for example fossil energy such as oil, and that the limited ability for the atmosphere to absorb greenhouse gases causes global warming. More recently, in 2016, Stuchety et al [2] explain that the large economic growth over the past 30 years, when measured by GDP, has been driven largely by depleting natural capital and to illustrate this point they cite "in 2015, we used a full 1.6 planets with most rich countries using between two and five times more than their share". [3]

As far as industry is concerned, improving operations is a critical enabler. Manufacturing theories such as lean manufacturing or the theory of constraints, among others, are essential pillars for operational excellence and resource productivity. In the context of above mentioned global dilemmas, industry accounts for 25.9% of all energy consumption in Europe in 2015 [4]. Whereas, in the same period the industrial sector in the US is responsible for 32% of the total energy consumption. [5]

This research aims to integrate sustainability and productivity aspects in manufacturing by applying lean, green and constraint management. To present the findings, this paper is structured into four chapters. Section 2 explains the scientific approach applied. The authors then present the current state of research regarding lean and resource-productivity in chapter 3. In section 4 the application of loss thinking in resource-productive operations is presented. Finally, the main findings are summarized and further research is suggested.

2. METHOD

The basis for this research is a literature search carried out in November 2016. Online databases like Google Scholar, ScienceDirect and Scopus are searched. The literature search addresses two different fields of research. First, in order to get insights in recent literature concerning improving operations following keywords and combination of these, are used: "lean", "green", and "efficiency". Second, to get information about limitations and constraints in manufacturing processes the online databases are searched with the keywords "constraints" and "theoretical limit". To refine results these keywords are always directly linked to the terms "production" or "manufacturing". Furthermore, reference lists of publications and selected literature concerning industrial practices regarding resource-productive operations are also considered. Finally, all literature expected as relevant and fully accessible was processed and included in this research.

3. CURRENT STATE OF RESEARCH

A lot of research has been conducted over the recent years in the fields of lean manufacturing, energy efficiency and cleaner production. This research builds on these efforts and develops an integrated view of resource-productive manufacturing through the extension with theoretical limit thinking.

Delimitation along production value chain

A systematic review of literature in the field of lean and green has been conducted by Garza-Reyes [6], concluding further research needs in six areas (1) compatibility, (2) amalgamation, (3) integration with other paradigms, (4) methods/indicators to measure their contribution and effect, (5) impact on organizational performance, (6) application across functions/industries.

This paper focuses on aspect number 3, the integration of lean and green with theoretical limit thinking and theory of constraints. Further limitations are the focus on the manufacturing sector and thereby on operations. In general, the manufacturing sector drives innovation within the field of lean and green research as well as in the development of working practices. Within the ongoing research, concerning the process of increasing the impact of lean and green applications, two main focus areas can be identified: (1) the macro and (2) the micro level. Research with the focus on the macro level considers the move from supply chains to supply circles (e.g., cradle-to-cradle and circular economy research). Whereas, the micro level focuses on operations or processes. [6] Considering the (simplified) life cycle of the material- and energy flow of a manufacturing company's product (gate-to-gate), this research deals with the processes/operations (thus, micro level) within a company and the needed energy flow for the production system (see figure 1).

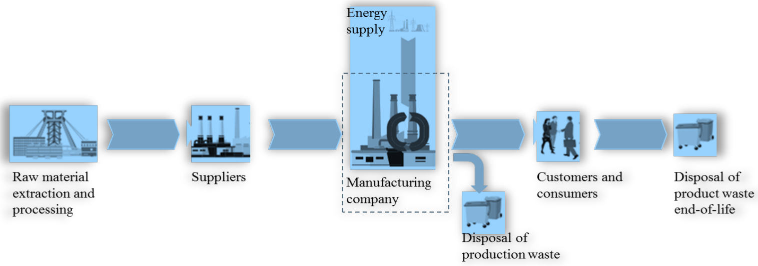

Figure 1 – Product life cycle [7]

Lean and green

As traditional lean thinking focuses on labor and asset productivity, this section shows that resource productivity and lean are synergistic and use same fundamentals. This research does not aim to discuss different aspects of lean thinking. Nevertheless, this section presents core principles of lean to gain a common understanding of lean and its overall goal(s).

» Classical lean

Womack, Jones and Rood, the authors of the book "The Machine that Changed the World" stated in 1990 that lean is in fact the most successful way of producing things. Reason for this very powerful statement are the two modes of implications of lean. First, lean supplies better products in a greater variety. Secondly, lean production provides more fulfilling and challenging work tasks for employees. [8]

The lean model, derived from the Toyota Production System, aims to reduce waste. Waste or muda are all operations, resources and even more in general, all work tasks and steps performed to produce a product that are not adding value. [9]

The seven types of waste according to the founder of lean production Taiichi Ohno are (1) overproduction, (2) waiting, (3) transportation, (4) overprocessing, (5) inventory, (6) motion and (7) rework and scrap. [10]

Lean thinking in short is about eliminating waste to maximize value and is based on following five core principles: [9]

1. Value: The end user defines the value of a particular product or service generated by the manufacturer. It is about providing the right goods and / or services in the right way. The critical first step in lean thinking is to define value as exactly as possible.
2. Value stream: The term "value stream" refers to all specific activities necessary to create a product or service (or a combination) from the initial concept to the delivery to the customer.
3. Flow: Flow, for example, involves the detachment of departmental and functional thinking towards the creation of a culture in which everyone makes a positive contribution to value creation.
4. Pull: Within the lean approach, services are only provided if they are asked for. Lean enables companies to produce exactly what the customer needs, when he needs it.
5. Perfection: The Lean concept consciously aims at the ideal state (zero faulty parts, infinite product variations, constantly reducing costs, etc.). The implicit sense is not to achieve these goals, but to continually strive for those targets. [8]

» Lean and green research

Heinen and Wulf state that the principles of lean manufacturing are a perfectly suitable basis for an energy and environment oriented production strategy [11]. Several independent studies confirmed that lean and green are highly synergistic. Dües concluded: "The research findings indicate that a Lean

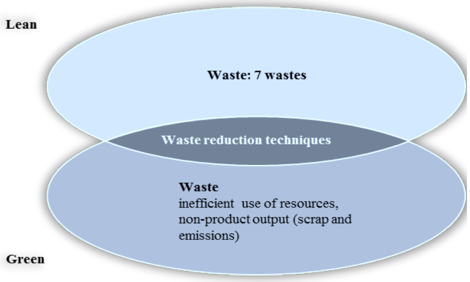

Figure 2 – Overlap of Lean and Green Paradigms [12]

environment serves as a catalyst to facilitate Green implementation. The integration of Lean and Green practices will bring benefits to companies and introducing Green as the new Lean is no longer a strong and unsupported statement. It is rather undeniable that the ultimate Lean will be Green." [12]

Hallam, Conteras found positive evidence that "lean is pushing green outcomes through operational waste reduction" [13]. Fercoq also confirms in his quantitative research that convergence of the concepts of Lean Manufacturing and Green Management. Specifically, Waste Reduction Techniques are considered one of the main areas of the overlap between the Lean and Green (see figure 2). [14]

Table 1 – Classic and resource-specific sources of waste can be targeted by lean [15]

Waste Categories and Examples	Result	Operations Examples
Overproduction Producing more volume than needed of a given product or generating reports with information that no one uses	Producing utilities that aren't used	Excess cooling water is sent to the plant, bypasses the heat exchanger, and is sent back to the tower
Waiting Waiting for approvals, reviews, or parts needed to perform the next step of the process	Energy is consumed even during production stops	During a production stop or shut down, conveyor belts, pumps, and fans are still operating even though no product is flowing through the process
Transportation Moving raw materials repeatedly, traveling between locations and handoffs	Energy is lost during transportation	Multiple air compressors are linked to pipes that have extensive leakage or large pressure drops occur in pipe networks
Overprocessing Producing a higher-quality product than the customer is willing to pay for	Energy consumption is deliberately set higher than the process needs	Operators create a safety margin to ideal settings of furnace temperatures higher than needed, production speeds and compressed air pressure
Inventory Accumulating excess stock, work-queue backlogs, open projects and tickets	Energy is lost in stored inventory and energy required to store products	Hot steel slabs cool too much prior to production or operators must heat or cool inventory in warehouses because of overproduction
Rework and scrap Producing products that don't meet quality standards or incomplete, error-filled documents	Resources are consumed by rework or scrap production	Improperly sized sinter is sent back to the beginning of the sintering process
Motion Walking between machines and workshops or searching for needed items such as files	Processes or pieces of equipment use resources inefficiently, although the equipment is efficient	Company uses high-quality, efficient boilers, exchangers, and VFDs but sets the oxygen level too high, which reduces boiler efficiency
Employee potential Failing to fully utilize employee skills or elicit ideas from the people who do the work	Company fails to capture employee knowledge to identify and reduce energy waste	Employees are not directly involved in developing energy-saving initiatives
Resource-specific		
Equipment efficiency Operating inefficient equipment	Higher energy use due to inefficient equipment (e.g. motors, compressors)	A boiler set to run at optimal levels loses energy because the stack lacks an economizer
System integration Failing to take advantage of available energies across different processes	Available energies (heat, cold, work, pressure) are being wasted	When products are heated for processing and cooled for storage, not using the hot product to heat nor using the cool product to chill

Hammer, Somers (see table 1) provide a specific overview of the translation of the lean types of waste to resource productivity and complement the classic lean waste categories with two additional, resource-productivity specific sources of waste: (1) Inefficient equipment, for example, legacy motors and pumps that are much less efficient than similar equipment designed more recently; (2) System integration, to avoid or recover energy that is put into a product only to be taken out again later in the process. For example, a product is heated with steam during production and then chilled with cooling water for storage [15] or using excess process heat of a refinery for city district heating. [7]

Theory of constraints and theoretical limit

Investigating the efficiency and optimization opportunities of a production system of a manufacturing company, many enterprises start continuous improvement initiatives with idea generation based on the current situation (also referred to as bottom-up brainstorming). An alternative, more aggressive approach to boost resource productivity is to take the theoretical limit as baseline [16]. Figure 3 illustrates the difference between the two approaches.

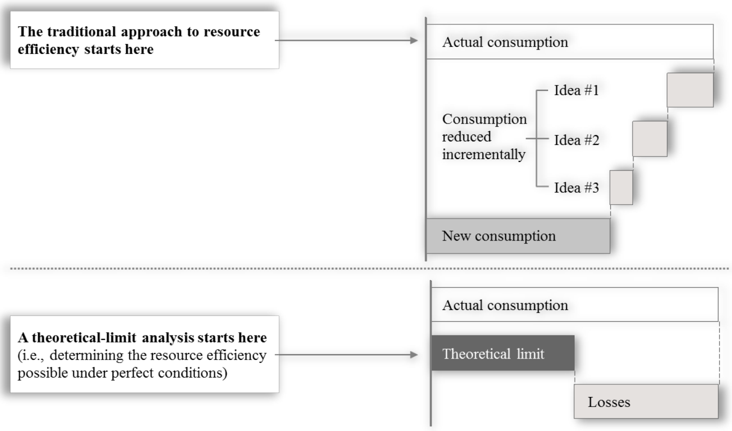

Figure 3 – Analyzing the theoretical limit exposes unseen losses [16]

To determine the overall losses and improvement opportunity, this research investigates further the actual consumption and the theoretical limit.

First, understanding the current performance (e.g., output, energy and material consumption, cost) is fundamental. Therefore a solid baseline comprised of facts and figures which can be measured and verified is required. The Efficiency Valuation Organization (EVO) [17] lays out an International Performance Measurement and Verification Protocol (IMVP) with focus on energy and water savings. While it is always relevant to quantify the starting point for improvements, in the area of energy investments, where energy service companies (ESCOs) provide energy efficient technologies and are paid by splitting the savings with their customers, this is even more important:

$$\text{Savings} = (\text{Baseline Energy} - \text{Reporting-Period Energy}) \pm \text{Routine Adjustments} \pm \text{Non-Routine Adjustments} \quad (1)$$

The second aspect is to explore the limits for optimization. Goldratt forged the "Theory of Constraints (TOC)" in his book "The Goal" in 1984 [18]. Rahman summarized the concept stating that every system must have at least one constraint. If this is not true, then a real system such as a profit making organization would make unlimited profit. Further, Rahman notified that the existence of constraints represents opportunities for improvement [19]. Jackson investigated constraint management further and differentiated between physical (e.g., process capacity) and non-physical constraints (e.g., market demand, supplier reliability, performance targets). Contributions of constraint management include providing a clear focus for the organization as well as emphasizing "generation of contribution margin through sales to improve profits rather than through cost reduction". One of the key challenges of this approach is an unstable environment (e.g. changes in demand and mix) causing the bottleneck to shift [20]. Each time Goldratt´s 5 step process, (1) identify, (2) exploit, (3) subordinate, (4) elevate, (5) go back to step 1, [18] would need to be gone through. This is one of the reasons, why it is also important to connect constraints management to strategic planning [20], as well as, recent research on agile manufacturing [21].

Investigating theoretical limits for resource productivity further, with an emphasis on energy, four different forms of energy contributing to industrial manufacturing processes can be distinguished [22]:

- Chemical energy: All materials contain chemical energy which can be transformed by e.g. combustion into other energy forms. Each chemical reaction needs at least the necessary activation energy to start this transformation process. This activation energy is identical with the theoretical limit. [22, 23]
- Electric and magnetic energy: Electric as well as magnetic energy is used in industry in various applications. Concerning the transformation of electric to other forms of energy the degree of efficiency depict certain limitations. [22]
- Mechanical energy: Subcategories of mechanical energy are kinetic energy; potential, elevation, or position energy; wave energy; elastic energy or sound energy. [22]
- Thermal energy: Physically every item with a temperature above absolute zero (-273.15°C) contains thermal energy. An addition of thermal energy expresses itself in a higher internal energy of the system to achieve this higher level of internal energy a certain activation energy is, at least, required. [22, 23]

In line with theoretical limit thinking, Kreitlein, et al. [24] developed a benchmark concept called E|Benchmark (see table 2). They define two ratios called EEV (Energy Efficiency Value) and EPE (Energy Process Efficieny) with the core idea of comparing and assessing energy efficiency in the production of technical products based on the relation of the minimum required energy to the actually consumed energy.

Theoretical limit thinking applies to all resources and not just energy. "A European Chemicals Producer learned by comparing the theoretical minimum amounts of raw materials required in each stage of production with actual consumption that up to 30% of their raw-material inputs were wasted". [25]

Table 2 – E|Benchmark definitions [24]

Definitions of minima		
Physical Minimum	The Energetic Physical Minimum (EPM) describes the minimum amount of energy required for chemical or physical laws to induce a transformation through a defined basic operation on or within the specific object.	$EPM = \sum_{i=1}^{n}(E_m)_i$ (2) E_m …input/output material spec.
Technological Minimum	The Energetic Technological Minimum (ETM) describes the energy demand, which is minimally required to perform a basic operation by a technology.	$ETM = EPM + \sum_{i=1}^{n}(E_t)_i$ (3) E_t … loss due technologies spec.
Real Minimum	The Energetic Real Minimum (ERM) describes the minimally needed energy demand to perform a basic operation by a technology with equipment. Additionally to the calculated value, the ERM describes the minimally required energy demand for a transformation process considering the state of the art.	$ERM = ETM + \sum_{i=1}^{n}(E_e)_i$ (4) E_e … losses due to equipment
Definitions of benchmark ratios		
Energy Efficiency Value	The Energy Efficiency Value (EEV) is used to compare and evaluate the energy efficiency of technical service provision. The minimum values of all three kinds of minima serve as a basis and are set in relation to the energy consumption measured (ECM).	$EEV_P = EPM/ECM$ (5) $EEV_T = ETM/ECM$ (6) $EEV_R = ERM/ECM$ (7)
Energy Process Efficiency	The Energetic Process Efficiency (EPE) is based on the modification of the process efficiency, which is described by the relation of value adding time to cycle time.	$EPE = \frac{Value\ adding\ energy}{Energy\ of\ a\ cycle}\ \%$ (8)

4. CONCLUSION

The understanding of loss thinking, in this research, as laid out in the previous chapters stems from lean and the equivalent of true value-add in resource productivity would be defined by the theoretical limit. Same as in lean, where it is more than just the tools [26], also in resource productivity, it is not only process design (i.e., equipment and technology) that matters, but also operational management.

Application of loss thinking to achieve resource-productive operations

Loss bridges reveal gaps between current performance and theoretical limit and can be applied for all resources. Figure 4 shows a loss bridge based on theoretical limit thinking with the aim of visualizing losses in order to find opportunities for improvement through lean and green management techniques.

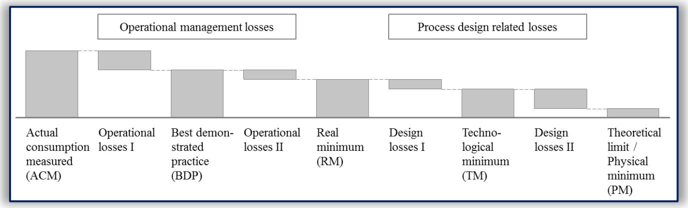

Figure 4 – Resource-productive operations loss bridge

In addition to the already defined terms, we add: Operational losses I, associated with process control (e.g., operator procedures, equipment settings) to reach Best Demonstrated Practice (BDP), the lowest documented, historical resource use for the current system design. Operational losses II cover the difference between BDP and potentially even better, not yet explored, operating parameters to come closer to the real minimum. Process design losses relate to equipment related losses (design losses I) and technology driven limitations (design losses II).

To illustrate the losses, the following three documented examples are illustrated: [7]

— A company for solid/liquid and dust filtration solutions went through a holistic process optimization effort tackling a variety of different losses such as material losses (e.g., filter media, auxiliary materials), losses during start-up/shutdown and overdosing. This was achieved through: (a) operational management solutions such as standardization of cutting patterns and the reduction of product variety, along with (b) process design improvements, e.g., automation of dosing and cleaning, as well as installing a new geothermal power plant with heat recovery and photovoltaics.

— A passenger bus manufacturer could achieve a reduction of 28% in energy demand in the period of 2011 to 2015 through the development and application of a "best practice guide" for energy management to reduce operational losses.

— In a move to tackle process design losses and adhering to Good Manufacturing Practice (GMP), a producer of printing ink, decided to implement a computer based raw material dosing system. With this measure they could eliminate losses related to human interventions (e.g. dosing errors, lack of accuracy) and reduce raw material losses by 8-10 tons per year.

Summary and outlook

In this paper we reviewed the need for resource-productive operations, summarized state-of-art management concepts in the manufacturing sector, and developed an integrated view through the application of a loss bridge. We conclude by highlighting the following critical enablers for applying loss bridges to investigate resource productivity in operations:

- A solid baseline, making use of the measurement and verification methods
- Use of theoretical limits as orientation point (i.e. true value add)
- Elimination of waste by tackling both operational management losses and process design losses
- Application of proven management processes from lean or standards such as ISO 50001

Further research needs include: (1) tools to help identify waste based on technical equipment data bases or factory data, (2) KPIs linking resource and financial implications together, and (3) online decision support methods based on big data.

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