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Improving material efficiency for ultra-efficient factories in closed-loop value networks

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Abstract

Infinite material circulation without losses in value or volume is a challenge for value networks, where materials are currently destroyed or lost. Today's waste prevention actions are predominantly one-dimensional and potentially create additional waste forms. To reduce waste in all dimensions, this paper first characterizes material waste forms, and then provides an analysis of their interdependencies. From these relationships a causal-loop diagram is derived, and the basis for a future system dynamics simulation model is described. The model will also examine their potential effect of waste minimization on energy consumption and productivity losses to assist manufacturers evaluate the effectiveness of waste minimization efforts.

This approach is developed within the "Ultra-Efficient Factory" project funded by the Ministry of the Environment, Climate Protection and the Energy Sector Baden-Württemberg to support efficient manufacturing in small and midsized companies.

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Keywords: material efficiency; waste minimization; multidimensional; system dynamics; circular economy

1. Introduction

Population growth and a rising standard of living for current and future generations can only be attained through sustainable economic growth [1]. Value creation in closed-loop value networks pursues this concept by building on the principle of infinite goods circulation without losses due to damage, or design change after initial manufacturing.

Currently, initial manufacturing is characterized by the production of various industrial waste forms, which reemerge in current recycling and remanufacturing practices [2]. These waste forms are diverse in nature and linked by driving factors in the production system. To eliminate these waste factors in initial manufacturing and prevent their reappearance in later remanufacturing processes, a strategy for preventing all industrial waste forms needs to be created.

The project "Ultraeffizienzfabrik – Verlustfrei produzieren in lebenswerter Umgebung" (Ultra-efficient factory – loss-free manufacturing in a livable environment) funded by the Ministry of the Environment, Climate Protection and the Energy Sector of Baden-Württemberg, Germany strives to improve the material efficiency of manufacturing sites, as well as reduce energy consumption and emissions. Ultra-efficiency describes a multidimensional optimum state, reached through minimal energy consumption, material consumption, and emissions.

2. Motivation

To support a circular economy material waste in factories and supply chains need to be prevented, allowing products to maintain their value beyond their initial usage phase [3].

Since material usage is a cost factor, the material efficiency of manufacturing processes has been subject of studies and mathematical optimization for the last 70 years. However, this work has primarily focused on one-dimensional optimization, i.e. preventing a single waste form (e.g. trim-loss optimization) [4]. This approach ignores the potential undesired effects of singular optimization on other waste forms (rejects, lubricants, tool wear) and energy consumption.

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To reach a multidimensional optimum of the system, the complex interdependencies of material waste need to be understood, quantified and modeled. A System Dynamics approach has been chosen to allow for future simulation of material waste reduction efforts and an evaluation of their effectiveness.

This paper provides the first step, describing the interdependencies between material waste forms in causal-loop diagrams. Finally, a method is presented for investigating the effectiveness of improvement actions on the entire system.

3. Definitions and State of the Art

3.1. Circular economies and closed-loop value networks

The transition to a circular economy, based on the approach of "sustainable development" has extensive implications for manufacturers and the market place. Economic growth must be achieved through improved resource productivity while maintaining the quality and quantity of natural resources. With the Cradle-to-Cradle concept, Braungart and McDonough describe sustainable products which can be either recycled as biological nutrients in biological cycles or technical materials, continuously recirculated through technical cycles [5]. These approaches can be viewed as a vision for material efficiency, with the material supply remaining at the same value level in the economic cycle with reduced wastage, lessened environmental impacts and while allowing for easy implementation in existing production structures [6].

3.2. Material efficiency

Industrial manufacturing has been the subject of time, material, and resource efficiency improvement efforts for over a century. Initially from an economic standpoint (time management) but also ecologically in the last 30 years. The term material efficiency has more recently developed into three pillars: material efficiency in production processes (waste minimization), maintaining finished product material over multiple product cycles (preventing downcycling), and a change in consumption patterns towards longer product use and correct product recycling [7].

Manufacturing process material efficiency (in the first pillar) can then be defined as the ratio of the amount of production input material to the required material in the finished product [8]. This definition works well for a single material flow at the process level (e.g. 1000 kg Steel coils-300 kg offcut = 70% material efficiency). However, the this measure is skewed with the inclusion of multiple material flows (e.g. plastic and metal components) and auxiliary materials flows (e.g. cutting fluids, solvents). While the percent lost material can be calculated (e.g. 30%), it is unclear which materials they are (metals, plastic, or cutting fluids), and difficult to compare system performance, since the monetary cost and environmental impact of this loss is unclear. To compare material losses in an inhomogeneous system, a carbon footprint can be used. This is the CO_2 emission equivalent of the lost material, including its disposal phase. Carbon footprint can be calculated using reference values in software databanks, but has been criticized for not fully describing the environmental impact of industrial waste or the economic burden [9].

3.3. One dimensional waste minimization

Material efficiency has classically been examined one-dimensionally on the process level (e.g. trim loss in a cutting process). From this work, waste minimization tactics have been executed for each individual waste form. These waste forms are offcut (trim loss) and byproducts, process rejects, transport scrap/inventory shrinkage, tool and auxiliary system wear and auxiliary material consumption [2].

Process rejects have been frequently divided into startup rejects, stemming from out of spec conditions in machine ramp up, and process rejects in normal operation [10]. Both refer to the depreciation of a part or component in a fabrication or assembly operation. Another form of startup rejects is the lost material during a product switch on non-dedicated continuous process lines in the process industry, when batch processing cannot be used [11].

Process scrap has been found to be heavily dependent on the manufacturing technology readiness, the tolerance of the process parameters, and the stability of the process environment. In the case of assembly errors, shift length, time of day, and the skill level of staff have to be considered.

To reduce startup losses, a move from batch processing towards continuous processing can be made, or change-overs can be performed without a full machine shutdown. To reduce losses in normal operation, process-monitoring mechanisms can be installed.

3.3.1. Preventing trim loss and byproducts

Offcut or trim loss and byproducts each describe a remainder of raw material that is separated from the product in a subtractive process (cutting, chemical separation) and alone does not have the potential to become a finished product, in contrast to rejects. The remaining pieces or matter can be used for a different product (smaller size or different composition). In a broader sense, chips from cutting/milling processes can also be considered offcut, though their occurrence is determined solely by the matching of cutting technology with raw materials [12]. The occurrence of offcut and byproducts is driven by the choice of process technology, specifically subtractive processes over additive. Subtractive processes, by definition, start with raw material compositions or geometries which are distant from final product specification. Subtractive technologies can be replaced increasingly by additive manufacturing technologies, though these are still limited by technological (e.g. surface quality) and machining costs [13].

The trim loss optimization problem or the cutting stock problem (CPS) is one of the oldest mathematical optimization problems, with the goal of determining the optimal plan to cut coils, or reels of paper, wood, metal, wires to size to fulfill a given customer requirement (a mix of sizes)[14]. The remainder at the end or edge of a coil which cannot be used is the off-cut or trimloss. Some authors also consider the tradeoff between minimal offcut and the resulting increased inventory and holding time due to early order launches to create a low-off-cut product mix. Other authors consider the additional complexity of joining two cut pieces in an assembly process downstream with minimal waiting time[15].

In some chemical processes, the mass ratios in which byproducts are produced is flexible, however, in other coupled productions, like the food industry, the mass ratios are static. In that case, creative marketing may be the only means to prevent byproducts from being deemed waste [16].

3.3.2. Preventing inventory shrinkage and transport damage:

Inventory shrinkage describes the depreciation of goods due to damage in storage (oxidation, molding, dust accumulation, deformation, spoilage, etc.) or obsolescence (large technology leaps) [17]. Efforts to reduce this include reducing and regulating inventory levels and reducing the throughput time.

Within the factory, product can be lost in handling or transport. Causes include the stability of the product itself and the chosen handling technology (fork lift, mechanical conveyors, etc.). To minimize this effect, regulation of forklift traffic speeds and loads can be used. For conveying powder products with conveyors, enclosures can be used to reduce dust from escaping.

3.3.3. Preventing tool wear

Tool life cycles are significantly shorter than machine lifecycles, due to consistent and heavy use. Studies have shown tool wear to be a function of production volumes, lot sizes, and maintenance [18]. Preventative actions include productive maintenance, tool design optimization, and process monitoring.

3.3.4. Preventing loss of cutting fluids, solvents

Secondary material flows like cutting fluids and lubricants are a large cost factor for companies with mechanical processes and also an environmental risk, though these materials are not contained in the finished product, they are necessary for some operations. For that reason, extensive work has been conducted to reduce cutting fluid loss from reservoir systems by individual loss type (e.g. splashing, work piece and chip fluid carry off, fluid mist, and leakages) [19]. Enclosures and excess fluid removal from chips and parts are common prevention measures, as well as preventative maintenance and dry cutting. Reservoir life can be shortened by contamination, wear, and lose effectiveness with age, while production factors like the frequency of use (production schedule, volume), maintenance, and reservoir environment also play a role [19]. Preventative maintenance activities including the use of additives and filters have been widely implemented.

Cleaners and solvents are mostly used during a machine set up, and are for that reason inversely proportional to lot size [20]. Their use has been effectively reduced in the process industry by optimizing product sequences and moving towards continuous processes [21].

3.3.5. Preventing internal/in-network packaging losses:

In a closed loop network, both disposable internal packaging as well as destroyed or lost reusable packaging can be deemed a material loss. Measures have been taken to introduce reusable packaging and generate acceptance for reusable packaging within supply networks, though this is often limited to certain regions of the world. One argument for disposable packaging is cleanliness requirements of the processes and inadequate cleaning facilities for reusable internal packaging. Productive maintenance actions can extend reusable packaging life.

3.3.6. Prevention of waste within closed loop value networks:

Transport scrap will become more prominent in circular economies, as the collective distance travelled over a product's many lifecycles will increase. Primarily, transport damage and lost parts in logistic processes hinder products from remaining on their original value-added level. To prevent transport damage, internal packaging in reusable and disposable forms has been used.

Waste in the hands of the user can describes either irreparable product damage or user failure to return end of use products due to inconvenience or general lack of acceptance for system. To prevent this, incentive systems or buy-back systems have been used as well as alternative business models (e.g. sharing) [22].

The waste forms occurring in remanufacturing, recycling, or refurbishing processes vary by the vertical integration (product recycling vs. material recycling). More industrial waste and downcycling (deprecation of value) occurs during material recycling, which is driven by the functional and aesthetic differences between the collected end of life products and those currently manufactured. Since material recycling takes the product to a low value-added level (downcycling), all of the manufacturing waste forms (rejects, trim loss, auxiliary material consumption) and those in raw material processing (byproducts) will occur. Approaches to minimize these waste forms include design for recycling and modular product design [23].

3.4. Multidimensional waste reduction

Approaches considering the linkages between material waste forms of different natures (cutting fluids and trim loss, rejects) were investigated in this detail only in a few cases e.g. Venkateswarlu et al, Alvandi et al [24][25]. Using simulation to examine the effectiveness of improvement efforts has been considered in the approach of Alvandi et al., though the occurrence of the waste forms is modeled as a function of the state of machine operation (ramp up, preproduction, production, changeover) without investigating other influence factors [25]. The improvement efforts were only technical in nature (retrofitting of the machines), rather than the factory operation and organization.

3.5. Waste Minimization Methods at the Factory Level

Many sustainability-focused value stream mapping approaches include the collection of material waste data, notably CO2 Value Stream, Multi-Layer Value Stream, and Sustainable Value Stream Analysis [2][26][27]. These methods provide an overview of waste forms within a company or network, and may assist in identifying waste reuse opportunities. However, this does not fulfill the purpose of value stream mapping with respect to reaching a global optimum for the system as a whole, by tuning the system to prevent waste production as a whole. This requires comprehensive knowledge of the interdependencies between different material waste forms as well as other waste forms (i.e. loss of productivity, energy consumption).

To assess the effectiveness of material efficiency efforts, the impact of each waste form has to be weighed economically and ecologically. To evaluate the efficiency of material utilization in companies, material-flow-oriented accounting methods have been developed in addition to classical management accounting [28], which also appropriate a cost portion to material use. Particularly material flow cost accounting [29] is designed for considering material flows and their losses. Resources or areas are modeled as individual facilities, to which the ingoing material as well as the outgoing product and lost materials are attributed. Through the separate monetary evaluation of the various flows, material waste can be identified for each facility from an economic perspective. However, the method unfortunately cannot offer any assistance in creating or evaluating improvement actions. Additionally, the facilities are defined so roughly that the effect of improvement measures within a resource and the outward consequences stay hidden. Diverse material waste forms are merely classified as waste.

4. Approach

To better understand the interdependencies between industrial waste forms, the waste forms are analyzed by the following criteria: occurrence frequency, occurrence location (process type and technology), occurrence environment, and market and product influence in Section 4. This characterization allows for the identification of driving factors. Using a system dynamics approach, causal-loop diagrams are then created. This lays the groundwork for a future system dynamics model and simulation of multi-dimensional improvement actions.

In Section 6, an approach for modeling the effectiveness of waste minimization efforts along with a brief preview of future work is provided.

5. Analysis of interdependencies between waste forms

In Fig. 1, the material waste forms in the factory are expanded to include those in a circular economy, and depicted as a leakage in the flow from raw unprocessed material to remanufactured post-consumer materials. This includes specifically the removal of product from the closed-loop flow during the use phase, during reverse logistics, or during remanufacturing. These include irreparable damage, incorrect disposal, missing components, and extreme wear. Some material waste forms, like transport damage and obsolescence, can occur anywhere in the economy but are only shown at their typical point of occurrence. For simplicity purposes, wear to factory buildings and machinery are not considered.

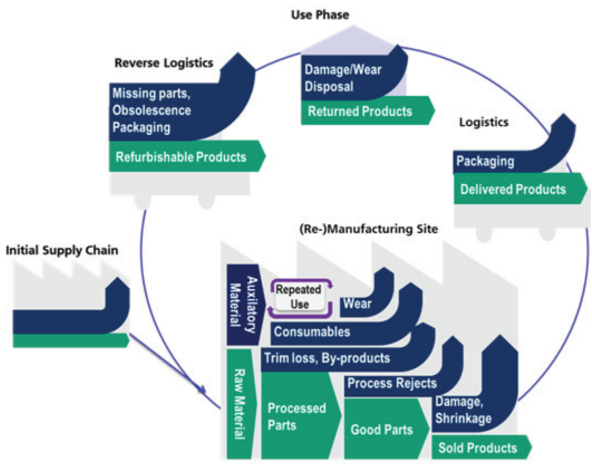

Fig. 1: Material Waste Forms in Circular Economies (In accordance with Erlach)[2]

5.1. Frequency and pattern of occurrence

In manufacturing operations, certain material waste forms occur with each machine tact, directly linking them to throughput (e.g. some cases of trim loss, cutting fluid loss, linear wear). Other waste forms like process rejects are also proportional to throughput, though they do not occur in each product cycle, e.g. 1 reject per 10,000 parts. Other waste forms are linked to the unit of raw material, for example the remaining offcut at the end of a steel coil when cutting blanks.

Similarly, there are many waste forms that are correlated with production lot sizes. These can be classified into two groups: first includes materials consumed in the set-up process, the second describes waste resulting from machine parameter deviations following the set-up.

The waste forms in the first category are associated with the method of product change over. One example is the use of cleaning products between product variations. Another example is the scrapped inhomogeneous product in continuous process in the process industry. The unifying factor for this group is that they occur during the set-up themselves, and are driven by the product sequence, i.e. more cleaning products during a change-over from black paint to white paint.

The second category describes the start-up losses resulting from the temporary departure from consistent process conditions. This occurs following set-ups, but also after machine break-downs and is not necessarily driven by product sequence.

5.2. Process type (continuous, batch, dedicated machinery or mixed use)

Product change overs in continuous processes, in contrast to batch processes, use less cleaning products and require no disruption to process parameters. However, as mentioned previously, an inhomogeneous product may be produced during the product change (scrap).

In fabrication processes, there are both benefits to dedicated and shared machinery. On dedicated machines, those running only one part type, there is no need for change over and the associated waste forms do not occur. For cutting processes, however, shared machinery has the benefit of a more diverse group of part geometries, making a trim loss minimization through nesting easier.

Lot production associated with shared machinery causes a higher level of inventory or work in process (WIP) within the factory, increasing the likelihood of inventory shrinkage due to damage or obsolescence.

5.3. Type of Process Technology (additive or subtractive)

As mentioned in Section 3, the choice of additive manufacturing processes over subtractive has large impact on material waste. The choice of processing technology dictates the occurrence of certain waste forms like offcut, chips, and byproducts. For example cutting and machining processes, are particularly wasteful, requiring cutting fluids which are lost in the process. Additive manufacturing techniques, like 3D printing would be the alternative, but are currently limited by their capability, cost, and energy intensity. Product design dictates processing technology choice.

Effect of manufacturing environment: The manufacturing environment also has an influence on material waste. Changes in temperature and contamination can cause inventory shrinkage and increase reject rates in normal operation. These also can lead to shortened tool or cutting fluid reservoir lifespan.

Within the warehouse and during transport, the temperature and air humidity play a large role in the waste rate, along with the use of protective packaging. The transport distances and the transportation method also influence waste production.

During the use phase, rough or incorrect use can also cause an end user to not return the products, while currently inconvenience and lack of acceptance are more significant.

5.4. Market influence

When end of use products are returned to the manufacturer, the required processing is dictated heavily by the difference between the end of use product and the next generation. Following significant product-design changes, material recycling and reintroduction at the beginning of the manufacturing process may be necessary. All of the manufacturing waste forms will reoccur (subtractive processes, large machinery, lot production). Due to the depth of the processing, transport from factory to factory may be necessary.

In a circular economy, the market demand has to be exactly matched with production throughput rates and the sum of products in circulation, otherwise inventory shrinkage can increase.

5.5. Product design: Inseparable materials due to poor product design/material selection

Refurbishment and remanufacturing is only possible if a basic decomposition of the product in parts can take place. If this is not possible, a more intensive process like shredding has to be used, which introduces the initial production waste forms into remanufacturing processes and may lead to downcycling.

5.6. Quantity

The amount of industrial waste is highly dependent on the product chosen, with spoilage shrinkage being prominent in food processing while in metalworking the amount of trim loss is more prominent. In the usage phase aside from minimal losses due to lack of user awareness, accidents, and transport damage, there should not be any other feasible loss of material. However waste in recycling processes can be much more significant and is mainly dictated by product design changes.

5.7. Resulting causal-loop diagrams

After summarizing the influential factors on each waste form, it is clear that there are a few driving factors in material waste within the scope of factory management:

- Shared machinery requires product change overs of and their associated wastes (startup losses, inhomogeneous product, and cleaning products). Their use is driven by cost pressure (fewer larger machines/ economies of scale) and product variety.
- Frequent changeover / small lot sizes cause more startup rejects, contaminated (inhomogeneous) products, more cleaning product consumption, however, less inventory shrinkage, less internal packaging materials.
- Subtractive processing technology linked to increased auxiliary consumption (cutting fluids, catalysts), occurrence of offcut and chips or byproducts
- Frequent product design changes make the last generation of product obsolete and hinder product recycling/remanufacturing. This increases material recycling (downcycling) and all forms of factory waste return during processing (byproducts, rejects, consumables).
- Poor product design (e.g. hard to disassemble, not modular) hinders product recycling and leads to downcycling

To roughly determine the coefficients of strength of each relationship, pair by pair comparison of the intensity of the links was completed. The generic causal relationships are summarized in Fig. 2 and split into the sphere of influence of the market and product development, factory management, as well as the sphere of the end user for transparency. These will be compared with data from the industry to form branch-specific causal diagram.

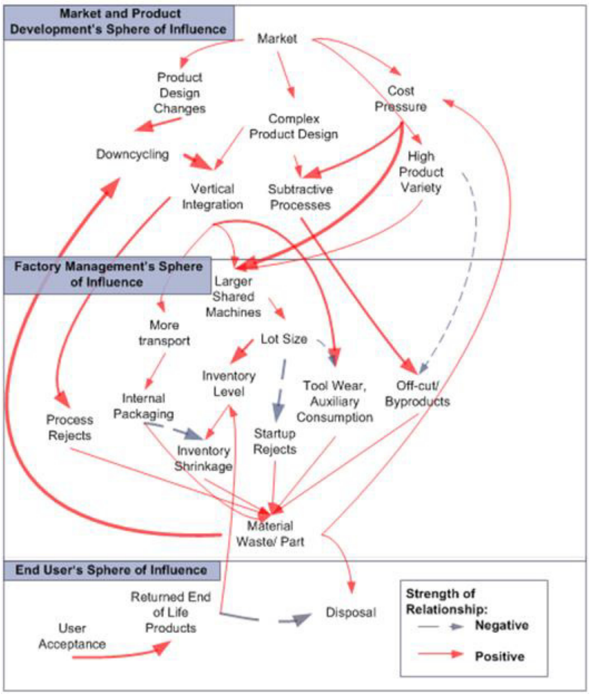

Fig. 2: Causal-Loop Diagram of Material Waste in Circular Economy without Weighted Relationship Strengths

5.8. Discussion of results

Following initial production, the most significant drivers behind the loss of material in a circular economy will be the market and product development, which introduce product design deviations from generation to generation, making it nearly impossible to simply collect, wash and repair products and reintroduce them on the market. The more drastic the product design changes are, the more destructive and heavy material recycling processes will be required. This means downcycling and the return of the initial manufacturing waste forms.

Other forms of waste like inventory shrinkage, incorrect use, and transport losses should reduce over time, as the circular economy is optimized to an ideal supply level and minimized distances to refurbishment centers, as well as greater acceptance from the public.

6. Approach to modeling the effectiveness of improvement efforts

Improvement efforts to increase material efficiency in the production cannot be executed in isolation, since they influence other parameters and aspects of the manufacturing environment. For that reason an economic and ecological evaluation of improvement actions with increasing causal complexity is challenge.

In the coming steps, a system dynamics model will be used to evaluate the effectiveness of improvement activities within this complex system. The following procedure will be followed in accordance with Sterman and Binder [30][31]:

- Integrate causal-loop diagram with causal loop diagrams of energy consumption and losses in productivity
- Validate strength coefficients in causal-loop diagrams
- Determine the impact of each waste (monetarily or with sustainability factor)
- Translate causal-loop diagrams into stock and flow models
- Determine and model improvement efforts

For validating the strength coefficients, historical data from companies within three specific branches will be used. This will provide the strength of the correlation between e.g. lot size and inventory shrinkage, which varies significantly between mobile phone manufacturers, metalworkers, and food processors.

To quantify the impact of each waste form and compare material waste with energy and productivity losses, both ecological and economic aspects will be considered. The monetary impact can be evaluated by the cost of lost materials in raw form, the added value before destruction/depreciation, and when applicable the further transport and disposal costs, minus the scrap price (residual value). To quantify the ecological impact, a CO_2 equivalent of the lost raw material, the utilized energy, and energy utilized for disposal can be used.

The resulting stock and flow diagrams will be integrated into a multi-level model, based on the evaluation approach for energetically transformable energy supply systems for manufacturing [32]. For the adaptation to material efficiency, a structurally similar model level will represent a simplified material flow- This additional level is inserted in the model in accordance with the method in ISO 14051 as an additional causal level. The calculated carbon footprint or cost associated with each material flow will be integrated into the base level.

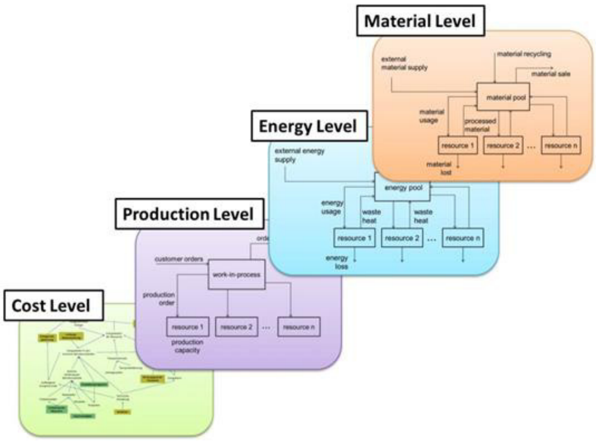

Fig. 3: Hierarchical Structure of Resource Pools

The causal levels (Fig. 3) contain cause-and-effect relationships on the same level or over multiple levels. The production level introduces a logistical dynamic into the model, where the effects of lot size changes or order sequencing can be represented. The higher system levels, which are described by the different perspectives of the production system, are projected onto the cost level. Cost causation models can support a more detailed calculation of the price of specific system characteristics.

If improvement actions to improve material efficiency are taken, they influence the resources and the material flow (Fig. 4) through behavior and parameter changes, reducing the targeted waste form but possibly increasing or triggering another form of material waste. This is also valid for changes to power consumption. These changes are to be simulated on each level of the model so that the changes in economic and ecological impact of the production system can be determined. In addition, the dynamics and the unknowns that exist in production systems with respect to future orders can be considered.

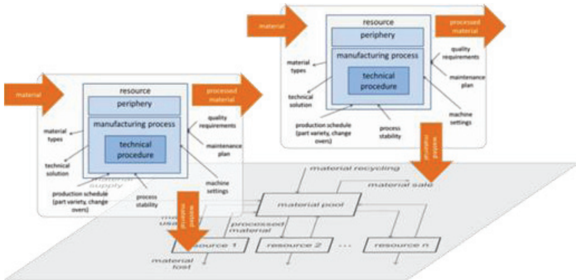

Fig. 4: Interacting Resources

7. Conclusion and Outlook

The analysis of the logical causal relationships between the material waste forms within a factory during initial production and during intensive remanufacturing processes has yielded lot size, product variety, process choice, and throughput as driving factors in industrial waste production. Some waste forms have a direct proportional relationship to production parameters (e.g. inventory shrinkage and lot size) while others have an inverse proportional relationship with the same parameter (e.g. startup losses and lot sizes). This makes the selection of all-in-one improvement measures difficult and simulation is needed to determine the cost effectiveness of improvement activities.

The intensity of the causal relationships shown will vary greatly from industry to industry and will lead to the formation of model variations e.g. a model of material waste in the food industry.

8. References

[1] Braun, A., Mandel, J., and T. Bauernhansl: Effective Use of Resources in Closed Value Networks. In: Bossomaier, Terry (ed.)u.a.: SESDE 2013: Proceedings of the 1st International Workshop on Simulation for Energy, Sustainable Development & Environment, Athens, Greece, September 2013. Genua, 2013. P. 12-15.

[2] Erlach, K., and E. Sheehan: Die CO2-Wertstrom-Methode zur Steigerung von Energie-und Materialeffizienz in der Produktion. ZWF Zeitschrift für Wirtschaftlichen Fabrikbetrieb 2014; 9. P. 655-658.

[3] Ellen MacArthur Foundation (2012), Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition, www.thecirculareconomy.org.

[4] Haessler, R., and P. Sweeney: Cutting Stock Problems and Solution Procedures. European Journal of Operational Research 1991; 54 (2); P: 141-50.

[5] Braungart M, and W. McDonough. Cradle to Cradle – Remaking the Way We Make Things, 1st Ed. London: Vintage Books; 2009.

[6] Greyson, J.: An Economic Instrument for Zero Waste, Economic Growth and Sustainability. Journal of Cleaner Production 2007; 15 (13-14). P. 1382-1390.

[7] Jackson, T.: Principles of Clean Production. Clean Production Strategies: Developing Preventive Environmental Management in the Industrial Economy. Boca Raton, FL: Lewis, 1993. P. 145-150.

[8] Cordoba, D., and A. Veshagh: Managing Eco Design and Sustainable Manufacturing. Re-engineering Manufacturing for Sustainability: Proceedings of the 20th CIRP International Conference on Life Cycle Engineering, Singapore 17 - 19 April, 2013. By A. Y. C. Nee. Singapore: Springer, 2013. P. 59-67.

[9] Franchetti, M., and D. Apul: Carbon Footprint Analysis Concepts, Methods, Implementation, and Case Studies. Boca Raton: CRC, 2013.

[10] Maran, M., Manikandan, G., and K. Thiagarajan. Overall Equipment Effectiveness Measurement: Weighted Approach Method and Fuzzy Expert System. IAENG Transactions on Engineering Technologies Special Issue of the International MultiConference of Engineers and Computer Scientists 2012. By G. Yang. Dordrecht: Springer, 2012. P. 231-245.

[11] Holloway, M., Nwaoha, C., and O. Onyewuenyi: Process Plant Equipment Operation, Reliability, and Control. Hoboken: Wiley, 2012.

[12] Todd, R., Allen, D., and L. Alting; Fundamental Principles of Manufacturing Processes. New York: Industrial, 1994.

[13] Ippolito R, and L. Iuliano: Benchmarking of Rapid Prototyping Techniques in Terms of Dimensional Accuracyand Surface Finish. CIRP Annals - Manufacturing Technology 1995; 44 (1). P. 157-160.

[14] Liberti, L., and N. Maculan.: Global Optimization: From Theory to Implementation. New York: Springer, 2006. P. 98.

[15] Arbib, C., and F. Marinelli: Integrating Process Optimization and Inventory Planning in Cutting-stock with Skiving Option: An Optimization Model and its Application. European Journal of Operational Research 2005; 163 (3). P. 617-630.

[16] Ockerman, H., and C. Hansen: Animal By-product Processing & Utilization. Lancaster, PA: Technomic Pub., 2000.

[17] Tompkins, J., and J. Smith: The Warehouse Management Handbook. Raleigh, NC: Tompkins, 1998. P. 845-850.

[18] Selaouti, A.: Co-ordinated Tool Maintenance and Production Planning and Control for an Integrated Production Management in a Process Chain for Precision Forging. Proceedings of the 6th CIRP-sponsored International Conference on Digital Enterprise Technology. By S. Baumgarten and R. Nickel. Berlin: Springer, 2010. P. 547-555.

[19] Adler, D., Hii, W., Michalek, D., and J. Sutherland: Examining the Role of Cutting Fluids in Machining and Efforts to Address Associated Environmental/Health Concerns, Machining Science and Technology 2007; 10 (1) . P. 23-58.

[20] Filipovic, A., Gowaikar, J., Olson, W., Pandit, S. and J. Sutherland, Characterization of Cutting Fluid System Dynamics, Proceedings of IMECE: Manufacturing Science and Engineering, ASME Bound Volume - MED 1998; 8. P. 389-395.

[21] Grundemann, Laura, Vera Gonschorowski, Norbert Fischer, and Stephan Scholl. Cleaning Waste Minimization for Multiproduct Plants: Transferring Macro Batch to Micro Conti Manufacturing. Journal of Cleaner Production 2012; 24. P. 92-101.

[22] Minner S, and G. Kiesmueller: Dynamic Product Acquisition in Closed-Loop Supply Chains. International Journal of Production Research 2012; 50 (11). P. 2836-2851.

[23] Kutz, M. Environmentally Conscious Mechanical Design. Hoboken: John Wiley & Sons, 2007.

[24] Alvandi, S., Bienert, G., Li, W., and S. Kara: Hierarchical Modelling of Complex Material and Energy Flow in Manufacturing Systems. In: Proceedings of the 22nd CIRP Conference on Life Cycle Engineering; Sydney, 2015.

[25] Venkateswarlu, P.: The Trim-Loss Problem in a Wooden Container Manufacturing Company. Journal of Manufacturing Systems 2001; 20 (3).

[26] Lourenço, E., Baptista, A., Pereira, J., and C. Dias-Ferreira: Multi-Layer Stream Mapping as a Combined Approach for Industrial Processes Eco-efficiency. Re-engineering Manufacturing for Sustainability: Proceedings of the 20th CIRP International Conference on Life Cycle Engineering,

Singapore 17 - 19 April, 2013. By A. Y. C. Nee. Singapore: Springer, 2013. P. 427-433.
[27] Badurdeenb, F., and W. Faulknera.: Sustainable Value Stream Mapping (Sus-VSM): Methodology to Visualize and Assess Manufacturing Sustainability Performance. Journal of Cleaner Production 2014, 85. P. 8-18.
[28] Kloock, J., Sieben, G., Schildbach, T. Homburg, C.: Kosten- Und Leistungsrechnung. Stuttgart: Lucius & Lucius, 2008.
[29] ISO 14051:2011: Environmental Management - Material Flow Cost Accounting. Berlin: DIN Deutsches Institut für Normung E. V., 2011.
[30] Sterman, J.: Business Dynamics: Systems Thinking and Modeling for a Complex World. Boston: Irwin/McGraw-Hill, 2000.
[31] Binder, T., Svensson, M., Haraldsson, H., Belyazid, S., and A. Vox: Developing System Dynamics Models from Causal Loop Diagrams. Proceedings of the 22nd International Conference of the System Dynamics Society: July 25-29, 2004, Oxford, England. By Michael Kennedy. Albany, NY: System Dynamics Society, 2004.
[32] Kuhlmann, T; and T. Bauernhansl: Method for Designing an Energy-agile Energy System for Industrial Manufacturing. In: Proceedings of the 22nd CIRP Conference on Life Cycle Engineering; Sydney, 2015.