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Modelling of bicycle manufacturing via multi-criteria mixed integer programming

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Abstract

Sustainable manufacturing considers the economic, environmental and social dimensions as equally important. For any product, like the common bicycles, a holistic view on the different life cycle phases has to be taken in order to ensure that resources are utilised adequately. Preferences on the three dimensions might lead to different selections of materials, used equipment or required education for fulfilling the considered objectives.

In a first approach, bicycle manufacturing alternatives are identified and modelled via bi-criteria mixed integer programming. The material usage is used to represent the economic dimension and the carbon dioxide equivalent is used to represent the environmental dimension. The computed supported efficient solutions provide reasonable trade-off solutions for the considered bicycle manufacturing problem.

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1. Introduction

Sustainability for human kind can be seen as the ability to meet its needs without a disruption to nature or society of all humans. Sustainability is interpreted into environmental, economic and social dimensions. A prerequisite that falls under the environmental dimension is that once non-renewable raw materials have been transformed into products, they may not be discarded but will have to be regained in product and material cycles. An alternative to reduce the use of non-renewable raw materials is to substitute them with renewable raw materials. The substitution can be carried out as long as it does not exceed the renewal rate. Pollution can only be created at the rate of its purification or neutralisation. An economic requirement is that wealth has to be generated without breaking the environmental prerequisite. Lastly, having a system in place where only a small proportion of the world’s population benefits from the global resource, has access to social support, knowledge and enjoys well-being has to be abandoned in order to adhere to the social necessities of sustainability [1], [2].

A product’s life-cycle usually starts with the idea of how the product should look like, the product design. From that point the product has to be realised. The realisation of a product traditionally begins with raw material extraction, raw material processing, manufacturing (including assembly), usage (including distribution and retail) and at the point in time when the product is obsolete an end-of-life strategy has to be exploited in order to reclaim the materials in the obsolete product [3]. Recycling and remanufacturing are two end-of-life strategies. Recycling is focused on material recovery, whereas remanufacturing is aimed at component recovery [4].

Attempts to manufacture in a sustainable manner require focusing equally on the three dimensions of sustainability. The example in this paper shows efficient computed solutions that provide reasonable trade-off solutions for a considered bicycle manufacturing problem. The material usage is used to represent the economic dimension and the electricity consumption that is translatable into carbon dioxide equivalent is used to represent the environmental dimension.
2. Manufacturing of bicycles

2.1. Modern manufacturing

Equipment and tools are required for manufacturing procedures. They come in various shapes and sizes depending on the process requirements. Where high manufacturing output, high level of quality and high level of precision is required, e.g. as with automated stamp presses, CNC machine centres, automated heat treatment systems, automated laser cutting machines and automated coating systems, the equipment tends to be capital intensive. Capital intensive refers to equipment that binds capital. Automated equipment usually requires highly qualified workers due to the complexity of operating the equipment. Small handheld tools, e.g. files, hammers, hand drills and hand saws are labour intensive. They do not yield the same output, lower level of quality and lower level of precision but often have little requirements on qualification [5].

2.2. Bicycle parts and final assembly

The common bicycle contains around 200 parts that are produced by different types of manufacturers, all around the globe. From the individual parts, subassemblies are jointed and from them the assemblies as shown in Fig.1. These assemblies are the frame, the rear wheel assembly, the pedal set, the front wheel assembly, the front set, the break set and the seat set.

The bicycle’s supply chain is to a large extent push driven, i.e. component groups such as the rear wheel assembly, pedal set, front wheel assembly and break set are manufactured based on forecast in high volumes. The frame, the front set and the seat set have a more diverse competition, with a mixture of push and pull principles.

The frame is the main assembly of the bicycle, acting as the main branding association force for the whole assembly. It can be made from various materials, e.g. steel, stainless steel, aluminium alloys, titanium, carbon fibre and metal inserts composite, wood and metal inserts, and bamboo and metal inserts composite. The frame is either made from lugs or mitered tubes. The manufacturing of the bicycle frame ranges from bespoke single made items to items that are carried out under preconditions of mass manufacturing, i.e. single design is manufactured in thousands of units annually. The front and rear wheels assembly (the rear wheel includes the cassette) contains parts and subassemblies, e.g. a rim, spokes, nipples, a hub, a skewer, a tire and a tube. These parts and subassemblies are usually manufactured under preconditions of mass manufacturing. The lacing and truing on the high end wheels is still a manual process, due to the precision and accuracy humans possess, required for these processes, compared to automated machinery. The pedal set contains pedals, cranks, axles, a crank set and a chain. The break set contains breaks, cables and leavers. Both the pedal set and the break set are usually manufactured under preconditions of mass manufacturing. The front set contains a fork set, a head set, a handle bar and a grip. Like the frame the front set is often custom made or mass manufactured but frames are often handmade independently of the fork, i.e. a final assembly of a bicycle could have a custom made frame but standard assemblies [6], [7].

3. Problem description and available data

The considered problem of manufacturing a bicycle frame comprises of two alternatives in raw material (bamboo or aluminium) and two alternatives in the degree of automation (automated with machines or manual/mechanised) with respect to the aluminium frame as seen on Fig. 2. The transformation of the respective raw material into a frame can be considered as an ordered procedure chain. The respective procedure chains for bamboo and aluminium do not overlap even if some procedures are labelled the same because different tools are needed for the respective material yielding different costs, scrap rates, energy consumptions etc. The procedures applied within the aluminium chain might be performed in an automatic way via machines or in a mechanised/manual fashion yielding two alternatives for each procedure (indicated by two arrows within the aluminium chain in Fig. 2). Each procedure/execution alternative induces a scrap rate which expresses the amount of waste (in percentage) that is incurred by executing this procedure. The overall monetary costs involve investment costs, maintenance costs, consumable costs and labour costs [8]. Energy consumption is used as an indicator for environmental impact. Readily available emission factors can be used to calculate the average CO2 emission based on respective national electricity production [9]. The emission associated with the production of the raw materials is currently not included.

Data on required processes, e.g. processing time, equipment cost and energy consumption was gathered through several workshops collected by master’s students and experts in the bicycle frame building industry. On-the-job data was collected for the construction of the two mechanised alternatives. Similar annual production capacities might be
acquired with a different selection of equipment, i.e. processing time, total cost and variable cost would be different [6]. A certain fixed cost including initial investments for acquiring machines and tools is linked to each procedure alternative. If the input number of a procedure alternative \( p_a \) exceeds the maximal annual production capacity of \( p_a \) by a factor of \( k \), then the fixed cost of \( p_a \) in the cost function is multiplied by a factor of \( k \) since it is assumed that in order to fulfil the production needs, machinery and tools need to be available \( k \) times. An additional input value \( n \) is given by the user representing a lower bound on the number of frames that need to be produced.

![Fig. 2: Procedural diagram for the manufacturing of three types of bicycle frames](image)

### 4. Mathematical model

#### 4.1. Bi-criteria mixed integer formulation

The above model is incorporated into a bi-criteria mixed integer program as follows: For each material alternative (bamboo, aluminium-manual, aluminium-automated) and for each procedure (e.g. cutting, bending and filing) a non-negative (integer) variable \( x_{m}^{p} \) is introduced representing the number of frames of material alternative \( m \) processed by procedure \( p \). The impact of scrap rate \( s_{r}^{p} \) to each procedure \( p \) with respect to material \( m \) is incorporated into the model as follows:

\[
x_{m}^{p+1} \leq (1-s_{r}^{p}) \cdot x_{m}^{p} \text{ for bamboo related variables and}
\]

\[
x_{am}^{p+1} + x_{aa}^{p+1} \leq (1-s_{r}^{am}) \cdot x_{am}^{p} + (1-s_{r}^{aa}) \cdot x_{aa}^{p} \text{ for aluminium related variables where } p+1 \text{ is the subsequent procedure of procedure } p \text{ in the chain.}
\]

For example, the number of (unfinished) bamboo frames that are allocated for procedure ‘mitering’ is less than or equal to the number of (unfinished) frames allocated for procedure ‘cutting’ times the yield rate (which is 1 minus the scrap rate) of procedure ‘cutting’ (see Fig. 2). For aluminium we take into account that each procedure can be executed in an automatic fashion or a manual/mechanised way generally leading to two different yield rates.

The input parameter \( n \) representing a lower bound on the number of frames that need to be manufactured, is incorporated into the model as follows:

\[
n \leq x_{man}^{coat} + x_{mat}^{coat} + x_{aam}^{coat} \text{ where the respective variables represent the number of frames after executing the procedure ‘coating’ (being the last procedure in the considered chain) with regard to the different material alternatives bamboo, manually processed aluminium and automatically processed aluminium.}
\]

The inequality ensures that the number of manufactured frames is at least \( n \). (In fact, since we minimize the objectives, the number of manufactured frames will be \( n \)).

Linked to each variable \( x_{m}^{p} \) is a non-negative integer variable \( y_{m}^{p} \) and inequalities of the form:

\[
\text{max}_{cap}^{p} \cdot y_{m}^{p} \geq x_{m}^{p} \geq \text{max}_{cap}^{p} \cdot (y_{m}^{p} - 1) \text{ where } \text{max}_{cap}^{p} \text{ is the maximal annual production capacity of procedure } p \text{ with respect to material alternative } m. \]

Linked to \( y_{m}^{p} \) are certain fixed costs denoted by \( \text{fix}_{cost}^{p} \). The value \( \text{fix}_{cost}^{p} \cdot y_{m}^{p} \) enters the monetary cost function as an addend modelling the need to invest into enough machinery and tools to be able to fulfil production requirements. The whole monetary cost function is the sum of above fixed costs together with maintenance costs, consumable costs and labour costs. In other words,

\[
c_{1} = \sum_{p,m} (\text{mainte}_{cost}^{p} + \text{consum}_{cost}^{p} + \text{labour}_{cost}^{p}) \cdot x_{m}^{p} + \text{fix}_{cost}^{p} \cdot y_{m}^{p} \text{ where the sum iterates over all procedures } p \text{ and material alternatives } m.
\]

The second considered objective accounts for the overall energy consumption:

\[
c_{2} = \sum_{p,m} \text{energy}_{cost}^{p} \cdot x_{m}^{p} \text{ where the sum iterates over all procedures } p \text{ and material alternatives } m.
\]

The whole model can be compactly written in the form of a bi-criteria integer linear program:

\[
\min (c_{1}^{T}x, c_{2}^{T}x)
\]

s.t. \( Ax \leq b \),

\[
x \geq 0,
\]

\[
x \in \mathbb{Z}^{n} \times \mathbb{R}^{n}
\]
4.2. Methodology

Considering several objectives \( c_1, \ldots, c_k \), in general, one cannot expect to find a feasible solution that optimises all \( k \) objectives simultaneously. (The corresponding point in objective space of such a generally hypothetical solution is called ideal point.) Instead, one has to deal with trade-offs. A solution \( x \) is denoted efficient if there exists no other feasible solution \( y \) such that \( c_i^y \leq c_i^x \) for \( i = 1, \ldots, k \) with a strict inequality for at least one \( i \). The image \( Cx \) of an efficient solution is called non-dominated point. (A point that is not non-dominated is called dominated.) A decision maker is supposed to base his decisions only on non-dominated points, since a dominated point can be improved in at least one objective without worsening the other objective values. For multi-criteria mixed integer problems one can distinguish between non-supported efficient solutions and supported efficient solutions. The latter are characterised by the possibility of computing them via weight vectors and scalarisation. For a supported efficient solution \( x \) there exist a positive weight vector \( \lambda \) such that \( x \) is an optimal solution to the scalarised single-objective problem \( \min \lambda^T c x \) such that \( x \) is a feasible solution. For a more extensive review of multi-criteria optimisation we refer the reader to [10] and [11]. In the following, we restrict the computation to the supported efficient solutions because they already constitute solution alternatives to the respective optima of each individual objective and suffice to show that a decision maker generally has a choice of finding reasonable compromises with respect to sustainable bicycle manufacturing problems.

4.3. Numerical results

Figure 3. depicts the supported non-dominated points for the above bi-criteria mixed integer linear program with a lower bound value of 100 for the number of manufactured frames. The corresponding supported efficient solutions do not differ much with regard to the number of produced bamboo frames which circles around 85 for all solutions. This follows from the comparatively small value of the input parameter \( n \) which makes most of the automatically executed aluminium based procedures unalluring due to their high fixed costs. The differences obtained in the supported efficient solutions are mainly based on perturbations for the remaining aluminium based procedures. The ratio of monetary cost increase and energy consumption decrease is almost constant for the four economically best points (corresponding to the four left-most points on Fig. 3). After that it strictly increases implying that an improvement in the environmental dimension gets more and more expensive.

Figure 4. depicts the supported non-dominated points for \( n = 1000 \). The solutions produce either a number of bamboo frames around 848 or no bamboo frames at all. The range of automatically executed aluminium procedures is bigger than for \( n = 100 \) because the investment costs for machinery necessary for automatically executed procedures might pay off for some procedures in this case. The ratio of monetary cost increase and energy consumption decrease has similar characteristics as the case \( n = 100 \), although less strongly increasing for the right-most points.

Figure 5. depicts the supported non-dominated points for \( n = 5000 \).
Figure 5. shows the supported non-dominated points for the manufacturing problem with \( n = 5000 \). This case differs from the previous two in the number of supported efficient solutions and their characteristics. The number of supported efficient solutions is smaller and the ratios of the monetary cost increase to the energy consumption decrease are much steeper. Four of the five supported efficient solutions avoid producing any bamboo frames relying on automatically executed aluminium procedures implying that the investment cost pay off for an assumed \( n = 5000 \). Interestingly, two of the supported non-dominated points are relatively close to the ideal point with one of the corresponding solutions being the exception producing (approximately 4230) bamboo frames. The other solution uses significantly different procedures involving no bamboo manufacturing. However, both of them come relatively close to the ideal point which is a surprising and interesting outcome (for a decision maker).

5. Conclusions

In each of the above middle sized instances there exist several supported efficient solutions and non-dominated points, respectively, despite the individual optima to each objective giving a potential decision maker a relatively good freedom of choice. In the single objective case of considering only economic performance, a decision maker would have selected the left most point in Fig. 3, Fig. 4 and Fig. 5. With regard to a paradigm change towards sustainability, the environmental dimension cannot be neglected, making the whole set of efficient solutions a basis for decision making. Hence, the bigger and wider spread the set of available efficient solutions is, the more options of finding a convenient decision for a present manufacturing problem is enabled. All three instances provide a proper curve (see Fig.3, Fig. 4 and Fig.5) of supported non-dominated points that is not obvious from observing the raw data. These results indicate that it is worthwhile to compute the whole set of efficient solutions instead of heuristically looking for a single (lower environmental impact) alternative to the current economic optimum.

The graphs also show significant trade-offs between the environmental and economic dimensions, indicating that a lower environmental impact solution requires investment need and does not come for free.

6. Outlook

The presented case study is a part of a bigger ongoing study on how to incorporate the economic, the environmental and the social dimension into manufacturing practices. Currently it covers the manufacturing of one component (the bicycle frame). The project collaboration aims at modelling a whole life-cycle of a bicycle, including raw material processing phase, manufacturing phase, assembly phase, use phase and reutilisation (e.g. reuse, remanufacturing and recycling) phase. Transportation and logistics will be included at each phase. The manufacturing phase aims at including main bicycle components (e.g. wheel sets, front set, saddle set and drive set). Furthermore, the social dimension shall be incorporated into the model via a third objective.

The goal from a mathematical point of view is the computation (and visualisation) of all supported and non-supported efficient solutions and corresponding non-dominated points for an arbitrary number of objectives. The challenge is to incorporate algorithmic approaches for computing the non-supported efficient solutions.

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8. References

[1] Seliger G. Sustainability in Manufacturing. Berlin: Springer Verlag, 2007.
[2] Jackson T. Prosperity without growth? The transition to a sustainable economy. Sustainable Development Commission. 2009.
[3] Thierry MC, Salomon M, Van Nunen JA, Van Wassenhove L. Strategic issues in product recovery management. California Management Review. 1995; 37(2): 114-135
[4] The association of German engineers (VDI). VDI 2343 - Recycling of electrical and electronic equipment; Principles and terminology. Berlin: Beuth Verlag, 2001.
[5] Lotter B, Wiendahl H-P. Changeable and Reconfigurable Assembly Systems. In ElMaraghy, H. A. (Ed.) Changeable and Reconfigurable Manufacturing Systems. London: Springer. 2009: 127-142.
[6] Steingrímsson et al. Workshops on processes, processing times, equipment, tools and techniques used to manufacture bicycle frames: J.G. Steingrímsson, Editor. Berlin: TU-Berlin. 2013.
[7] Wilson DG. Bicycle science. 3rd Edition. Massachusetts: The MIT Press, 2004.
[8] Lanza G, Stoll J, Stricker N, Peters S, Lorenz C. Measuring global production effectiveness. In: Proceedings of the forty sixth CIRP conference on manufacturing systems 2013. 2013.
[9] European Union. How to develop a sustainable energy action plan – Guidebook. Part 2. Belgium: European Union. 2010.
[10] Ehrgott M., Multicriteria Optimization, Springer 2005, 2nd Edition
[11] Przybylski A., Gandibleux X., Ehrgott M., A recursive algorithm for finding all nondominated extreme points in the outcome set of a multiobjective integer problem. In: INFORMS Journal on Computing, Volume 22, 2010.