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Herausgegeben vom
Konrad-Zuse-Zentrum für Informationstechnik Berlin
Takustraße 7
D-14195 Berlin-Dahlem

Telefon: 030-84185-0
Telefax: 030-84185-125

e-mail: bibliothek@zib.de
URL: <http://www.zib.de>

ZIB-Report (Print) ISSN 1438-0064
ZIB-Report (Internet) ISSN 2192-7782

Identification of trade-offs for sustainable manufacturing of a Bamboo Bike by System Dynamics

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Abstract

We develop a generic System Dynamic model to simulate the production, machines, employees, waste, and capital flows of a manufacturing company. In a second step, this model is specialised by defining suitable input data to represent a bicycle manufacturing company in a developing country. We monitor a set of sustainability indicators to understand the social, environmental and economic impact of the company, and to estimate managerial decisions to be taken in order to improve on these criteria. We show that the social and environmental situation can be improved over time without sacrificing the economic success of the company's business.

Keywords: System Dynamics, Modelling, Life Cycle Sustainability Assessment, Sustainability Indicators

1. Introduction

Business as usual is not an option for preserving competitive advantages of leading industries. Hence, a transformation to sustainable value creation is needed. Such transformation processes involve many interventions and may lead to interactions not foreseen. Mathematical optimisation will be linked to sustainability indicators and hence can be a useful tool to identify the major influencing parameters to support decision makers. The foremost goal seems to be the generation of wealth in global value networks. This can only be done by taking into account the interconnections of social, environmental, and economic constraints. Therefore, the questions arises how sustainable manufacturing embedded in global value creation proves to be superior to traditional paradigms of management and technology. One of the main tasks is to reduce the physical resource and energy consumption during the productions of goods, while simultaneously maintaining the ability to increase economic wealth. Human wellbeing and securing human health become a vital task, which can be achieved by learning and teaching for a global community culture. The lifestyles of upcoming and also developed communities have to change to ensure a resource use within accountable environmental, economic and social boundaries.

As main tool of our analysis, we apply mathematical simulation techniques. The description of natural phenomena using mathematical models has a long history. The development of modern analysis by Newton and Leibniz in the 17th century is an attempt to assess physical effects using a mathematical description. A prominent example for the analysis of economic and environmental resources is the System Dynamics (SD) model World3, developed by Meadows et al.(1972).

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The basis for the derivation of an SD model is the definition of the model's scope. It is necessary to clearly define the application area of the model and, equally important, to describe what the model should not represent. When interpreting and analysing the simulation results, it is important to understand what conclusions are supported by the model. Therefore an agreement right from the beginning of the modelling process on the intended purpose and the goal needs to be achieved. During this process the stocks (or aspects in our application) will be defined as building blocks of the SD model.

The SD models are all numerically solved by simulation techniques, where the evolution of the system states over time is determined by the given parameters and their functional relationships.

Sustainability indicators consider all three dimensions of sustainability and do not focus on the environmental issues alone (Bell & Morse 2010). To measure the multidimensional sustainability of a given system, two approaches are possible to identify the right set of indicators: top-down and bottom-up. The first is used here and focuses on a generic base, where the system can be seen without limitations of data availability, the latter from the process or product perspective. The sustainability targets define the frame, which then is specified via the sustainability criteria. Parris and Kates (2003) made a review on existing measuring initiatives of sustainable development indicators and proposed a 2x3 taxonomy of goals. On the one hand there are the three major categories, which should be sustained: nature, life support systems, and community. On the other hand there are the three categories, which should be developed: people, economy, and society.

The sustainability target has been set to measure the sustainable development of global value creation networks while creating wealth and prosperity now as well as in future. In this paper, this is done using mobility as an example. The aim of this study is to create an SD model to simulate the sustainable manufacturing of bicycles, made from different resources (bamboo, aluminium) and include the supply chain (life cycle) where relevant.

2. Methodology

2.1 System Dynamics

“System Dynamics” (SD) was introduced by Jay Forrester in the 1950s to the 1970s (Forrester 1961; Forrester 1969) as a unified framework to describe time-dependent effects of complex systems having stocks, flows, and feedback loops. It received much public attention because of Forrester’s research on the “Limits to Growth”, which he conducted for the “Club of Rome” (Forrester 1973).

Deriving an SD model is a process that consists of multiple steps. The first step is the description of the model’s scope and goal, which is the basis for any subsequent modelling. As a next step, the relationships of a system’s indicators are represented in a causal loop diagram. Such a diagram reveals the dependencies among the indicators by showing if a certain indicator reacts directly while changes to some other indicator occur. This yields a qualitative model of the system, showing its basic underlying structure. The indicators are connected with arrows. These arrows have attached either plus or minus symbols, representing the growth or reduction of the indicator at the arrow’s head, depending on the growth of the indicator at the arrow’s tail.

In a final modelling step, the causal loop diagram is further refined into a stock and flow diagram. Stocks are able to accumulate or vanish over time, and flows describe the change rate of a stock. The stock and flow diagram is transformed into a set of equations, which are usually nonlinear difference or differential equations. In order to simulate such systems on a computer, it is necessary to discretise the differentials by, for example, an Euler- or a Runge-Kutta-Method (Betts 2009).

Because of the nonlinear relationships, the simulation of SD systems often shows a surprising, non-intuitive behaviour from the modellers’ point of view. Predicting the outcome of a simulation beforehand, or estimating the long-term behaviour of a system is also a difficult mathematical problem.

2.2 Sustainability Indicators

The problem is that there are too many indicators to use them all at once without cost explosions and pushing the time frame over the limit. The United Nations Department of Economic and Social Affairs (UN-DESA) came up with a total number of 132 indicators, aggregated to 46 key themes divided into the four aspects: Social, Environmental, Economic, and Institutional in their first publication, which have been reduced during the third revision by the Commission on Sustainable Development (CSD) to 96 with now only 14 themes or 44 sub-themes (UN-DESA 2007). The Global Reporting Initiative proposes 84 indicators, which are grouped into six indicator protocol sets (= themes) (GRI 2011). The German Strategy on Sustainability displays 21 themes associated with partly more than one indicator to come up with a total of 40 indicators (Bundesregierung 2012). Transforming so many given indicators into a stable scientific selection of a proper subset of indicators may be quite laborious and time consuming.

The following sustainability criteria have been selected to identify the sustainability indicator set:

- Environmental dimension: sustain life support systems, resource damage (energy and resource efficiency), terrestrial damage, marine and freshwater damage
- Social dimension: education of people, working conditions, productivity
- Economic dimension: development of economy, human capital, lifecycle costs, environmental externalities

The indicators will be used as entities for the system dynamics model to identify weak points and potentials for fast improvement.

3. Results and Discussion

3.1 The Generic Company Model

We develop a generic model to describe the internal relations of a small or medium sized manufacturing company. By setting certain parameter values it can be specified to a designated application area; we will below specialise it to a bicycle manufacturing company. Our model includes the following six stocks: 1) uneducated employees, 2) educated employees, 3) the company’s financial capital (budget), 4) the quality of its technical assets, 5) the product that the company produces, and 6) the waste as unavoidable by-product of the production (cf. Figure 1). The dynamical behaviour of each of these stocks s_1, \dots, s_5 is described by an ordinary first order differential equation of the form

$$\frac{ds_i}{dt} = in_i(t) - out_i(t) \text{ for } i = 1, \dots, 5.$$

As an example, the stock of uneducated employees can be increased or decreased by hiring (recruiting) or firing people, respectively. The amount of educated employees can also be varied in the same way. Additionally, it is possible to train uneducated employees, so that they become educated. This qualification measure reduces the number of uneducated employees and the company’s budget, and increases the number of educated employees. The working conditions in general also have an impact on the rate of people leaving the company. The number of uneducated and the number of educated employees are related to the productivity level, which increases with the number of educated employees. Each employee needs a machine tool to fulfil his duty. Hence their number has an influence on the growth rate of the quality of tech-

nical assets. Buying new machines is an investment; hence it reduces the available capital. Over time, the machines become older, and there is a normal decay process that leads to a reduction over the technical assets. The quality of the technical assets determines the energy efficiency, where higher quality assets are assumed to be more energy efficient. Furthermore, higher quality machines are more resource efficient. Both have an impact on the total consumption of energy and resource (raw materials). Productivity and resource efficiency both have an impact on the amount of produced waste, which is the growth rate of the total amount of waste. The company must get rid of the waste by waste disposal measures. The cost for waste disposal lowers the financial capital. The capital is further lowered by the total cost of energy (a product of the energy and the cost per energy unit), and the total cost of resource (a product of the resource and the cost per resource unit). The number of new products depends on the invested final resource and final energy, and the participating final number of employees. Also, the number of new products adds a certain proportional amount to the waste. New products go into the stock of all products, until they are sold on the market. When sold, they contribute to the company's revenue, which in the end adds to the growth of financial capital. In order to be able to sell products, the company needs to advertise them (or, more general, do marketing), which are also costs that reduce the financial budget. Finally, the budget is reduced by preserving the working conditions and by paying wages to the educated as well as to the uneducated employees, where the former usually get higher salaries.

All of the above relations are formulated as (in general) nonlinear algebraic equations on a time-discrete set of variables. As an example, the variable "resource" may be considered, which depends on "final employees" and "resource efficiency". Clearly, the more employees are needed, the higher the resource consumption as well as the lower the resource efficiency is, the higher the resource consumption. As constraints, we say that $\text{resource} = (\text{final employees}) / (\text{resource efficiency})$. The model consists of about 20 basic equations similar to the before mentioned, that are rolled out over a discrete time grid, leading to models with several hundred variables and constraints.

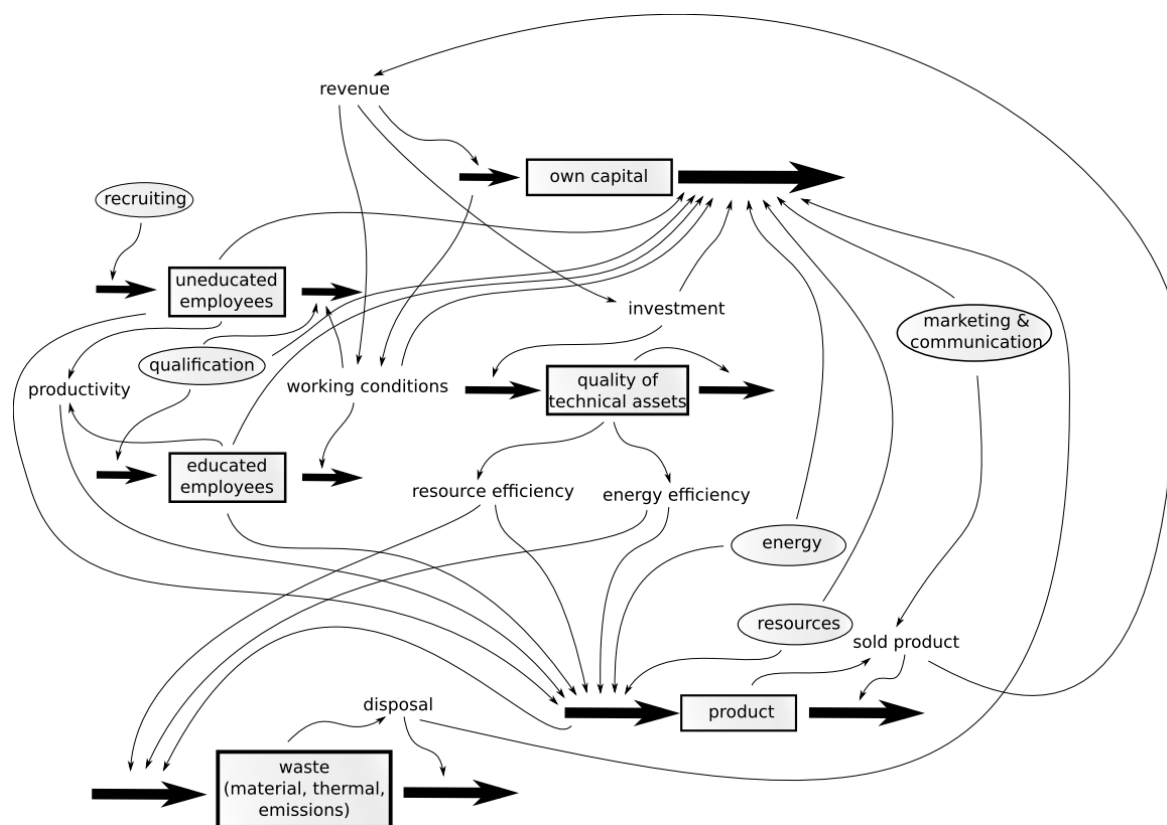


Figure 1: System Dynamic model for the generic manufacturing company

3.2 Relevant Indicators

The following indicators have been identified to play a significant role in the manufacturing process.

Table 1: Relevant Sustainability Indicators for the Bike Manufacturing (selection)

Dimension	Aspects	Indicators
environmental	climate change	global warming potential
		particulate matter formation (in atmosphere)
	marine & freshwater environment	eutrophication
		ecotoxicity
	terrestrial damage	land occupation
		acidification
	resource damage	water depletion
mineral resource depletion		
...

Dimension	Aspects	Indicators
social	education/ qualification	average hours of training per year per employee broken down by employee category
	working conditions	noise level on a working place
	productivity	labour costs broken down by qualification, gender, age group, and nationality

economic	economic business performance	sales generated with new products to total sales
		significant financial assistance received from government
	human capital	ratio of basic salary of women to men by employee category
	macroeconomic	adjusted net savings (% of GNI)
		gross fixed capital formation (% of GDP)
...	...	

3.3 Simulation

The model uses data from a Life Cycle Sustainability Assessment, carried out at the Chair of Sustainable Engineering, Technische Universität Berlin and partially published at the 2nd sustainability forum (Y.-J. Chang et al. 2012). The analysis evaluated two bicycles; one made with an aluminium frame and the other made with a bamboo frame. In a first step mainly data from Life Cycle Costing and greenhouse gas emissions are used to validate the model.

The virtual SME used as basis of the model has in total 24 employees and the manager (=owner):

Table 2: Employee Specification of the Virtual Bike Manufacturing SME

Employee Category	Number of Employee	Total Labour Cost per Hour
manager	1	80 €
secretary	0.5	25 €
account & sale	1.5	30 €
marketing	1	40 €
educated worker	6	21 €
uneducated worker	15	9 €

The workers can produce 30 bikes per day, which means to assemble one bicycle takes 292 min. By eight working hours per day and 220 working days per year the SME can produce 550 bikes per month in total. According to Chang (Y. Chang et al. 2013), the consumer purchase price is 945 €. For trading and shipping we assume there is a margin of 30% related to the manufacturing purchase price (= 246.40 €). The factory sells the bicycle for 616 €. The resource and energy efficiency starts with 90% to leave the option of improvement. Furthermore, the following assumptions were taken:

Table 3: Model Assumption for the Bike Manufacturing (per bicycle unless otherwise stated)

Model Elements	LCC [€]	GWP [kg CO ₂ e.]
seed capital	50,000	
overhead wages per hour	36.98	
educated wages per hour	17.50	
uneducated wages per hour	7.50	
recruiting; not needed so far	0	
cost of working conditions, e.g. noise reduction measures	15% of revenue	
cost of qualification	7.10	
cost of marketing	7.10	
cost of disposal	6% of resource cost	
product price	616.00	2767
resource cost	355.70	2646
energy cost	23.70	121

Since the model allows a good generation of own capital it was set to make changes after 2 years of operation (cf. Figure 3). The qualification is doubled to have more educated worker and the electricity is changed from average German Energy Mix to renewable electricity based on water power. The results are minimised CO₂e. emissions for the production as well as a stronger increase of productivity (cf. Figure 2).

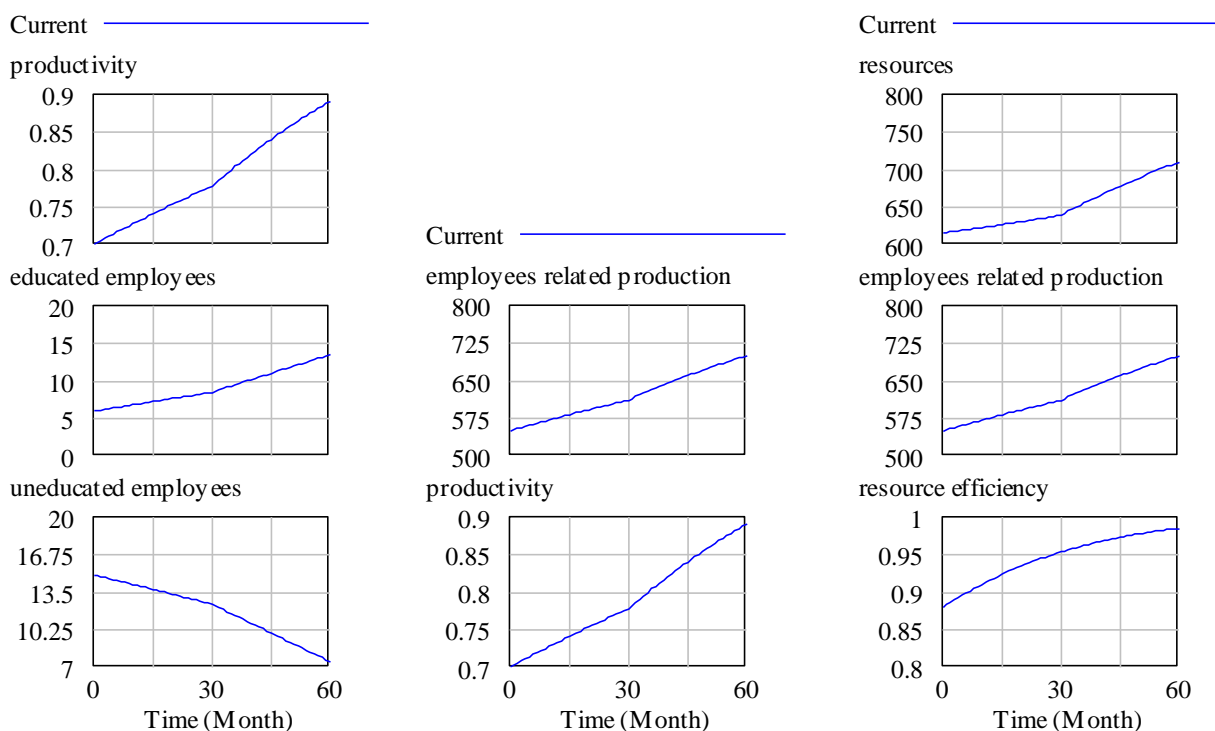


Figure 2: Relationship Productivity - Employees Related Production - Resources (consumption)

Here, the relationships among the different activities are visible. The productivity increases due to the undertaken qualification of uneducated workers. The increased productivity leads to an increase of produced bikes due to more qualified employees. The employee related production coupled with the resource efficiency results in an increase of resource consumption in a curved, non-linear way.

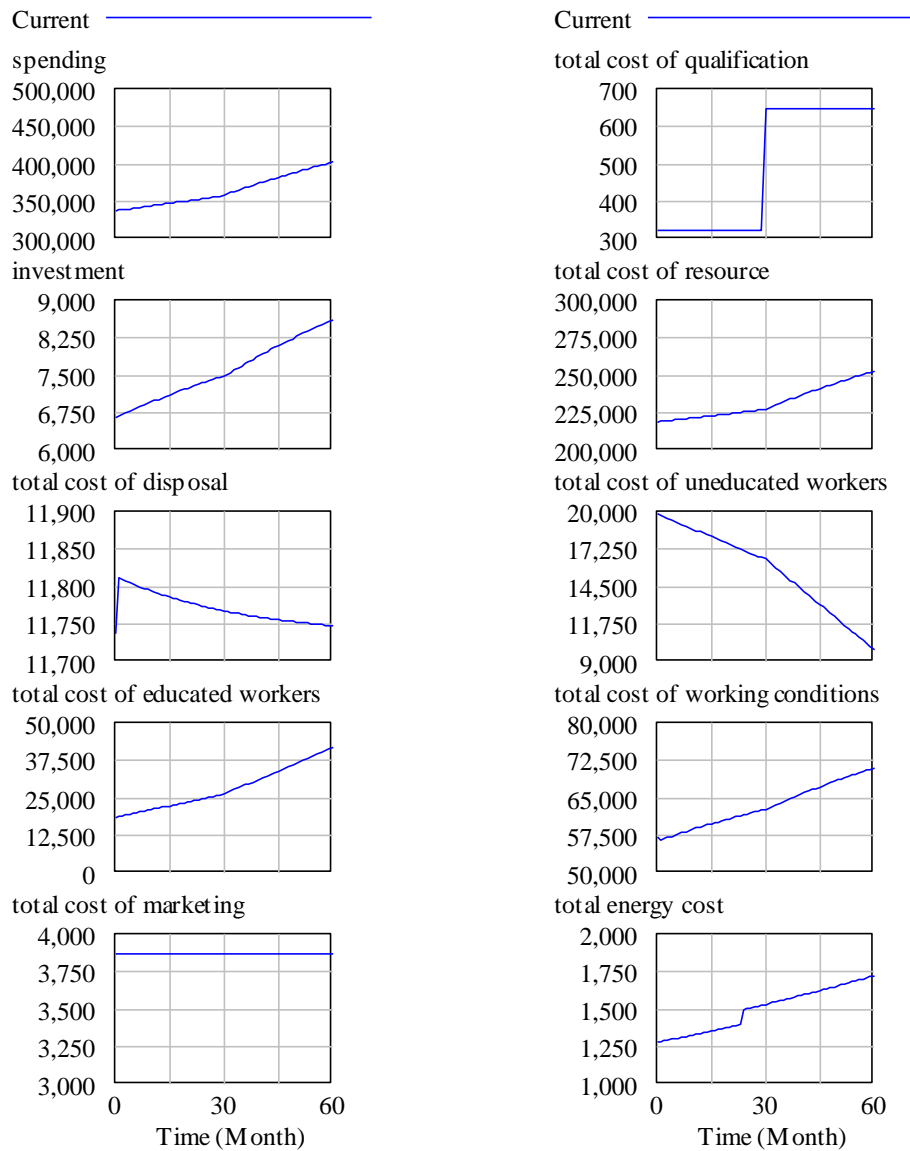


Figure 3: Summands related to spending the financial budget

4. Conclusions and Outlook

We developed a generic System Dynamic model to describe various aspects of a vital production company. Using an adequate set of data, we specialised this model to a bicycle manufacturing company. Our simulation shows that the company can accumulate financial resources over the first years of its existence,

and later invest this money resource to improve the skills of its employees, buy better machines, reduce waste, and still operate in an economically successful way.

The next steps will be the inclusion of other environmental impact categories like eutrophication, acidification, resource depletion etc. as well as the integration of more social aspects in other values than currency.

Acknowledgement

We gratefully acknowledge the co-funding of this work by the German Research Association (Deutsche Forschungsgemeinschaft, DFG), Collaborative Research Centre CRC1026 (Sonderforschungsbereich SFB1026). The forth co-author, Armin Fügenschuh, acknowledges the Konrad Zuse Fellowship under which he performed parts of this research.

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