



Konrad-Zuse-Zentrum
für Informationstechnik Berlin

Takustraße 7
D-14195 Berlin-Dahlem
Germany

R. SCHEUMANN A. FÜGENSCHUH S. SCHENKER I. VIERHAUS
R. BORNDÖRFER M. FINKBEINER

Global Manufacturing: How to Use Mathematical Optimisation Methods to Transform to Sustainable Value Creation

Supported by the DFG Collaborative Research Center **CRC 1026** "Sustainable Manufacturing - Ai Shaping Global Value Creation".

ZIB-Report 12-28 (August 2012)

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

Global Manufacturing: How to Use Mathematical Optimisation Methods to Transform to Sustainable Value Creation[§]

R. Scheumann* A. Fügenschuh** S. Schenker**
I. Vierhaus** R. Borndörfer** M. Finkbeiner*

Abstract

It is clear that a transformation to sustainable value creation is needed, because business as usual is not an option for preserving competitive advantages of leading industries. What does that mean? This contribution proposes possible approaches for a shift in existing manufacturing paradigms. In a first step, sustainability aspects from the German Sustainability Strategy and from the tools of life cycle sustainability assessment are chosen to match areas of a value creation process. Within these aspects are indicators, which can be measured within a manufacturing process. Once these data are obtained they can be used to set up a mathematical linear pulse model of manufacturing in order to analyse the evolution of the system over time, that is the transition process, by using a system dynamics approach. An increase of technology development by a factor of 2 leads to an increase of manufacturing but also to an increase of climate change. Compensation measures need to be taken. This can be done by e.g. taking money from the GDP (as an indicator of the aspect “macroeconomic performance”). The value of the arc from that building block towards climate change must then be increased by a factor of 10. The choice of independent and representative indicators or aspects shall be validated and double-checked for their significance with the help of multi-criteria mixed-integer programming optimisation methods.

[§]Supported by the DFG Collaborative Research Center **CRC 1026** “Sustainable Manufacturing – Shaping Global Value Creation”

*Department of Environmental Technology, Technische Universität Berlin, Germany; Email rene.scheumann@tu-berlin.de, matthias.finkbeiner@tu-berlin.de

**Zuse Institute Berlin, Takustr. 7, 14195 Berlin, Germany; Email borndoefer@zib.de, fuegenschuh@zib.de, schenker@zib.de, vierhaus@zib.de

1 BACKGROUND

In face of the challenges interwoven with the development of emerging countries, growing human population, resource availability, energy consumption, and climate change it is essential to change the value creation process to preserve also competitive advantages of leading industries. In addition the unequal distribution of wealth in different regions of the globe must be overcome. A step into that direction can be taken by shaping sustainable value creation of global manufacturing due to creating stable, socially, economically, and environmentally acceptable living and working conditions. One option to measure the impact of products is to use the life cycle sustainability assessment (LCSA) approach [1].

Today we face those manufacturing processes with different, sometimes dramatic local impacts in many parts of the world. The lifestyle of people in modern, highly industrialised civilizations with the consumption driven economy forces companies to transfer part of their production into regions with low requirements concerning environmental and societal regulations. The power, skills, and willingness to change current production and management processes at the level of enterprises and governments can help to achieve a higher level of equity. Nevertheless, the term sustainability is widely used on different levels, e.g. companies, institutions, and governments, but mostly only as a synonym for environmental activities [2]. It is now time to go beyond the focus of environmental issues alone and therefore include the socio-economic aspects in a so called triple bottom line approach by rising the following questions:

1. Which indicators are scientifically valid

to assess the environmental, economical and social dimensions of a sustainable value creation process?

2. How should these indicators be measured and aggregated to sub-themes, themes, and/or aspects?
3. How can the time-scale as well as the multi-criteria dimension of sustainability be optimised for decision making?
4. Which data are necessary for the implementation and is that data available?

Although this paper cannot give satisfying answers at this time to all these questions, it still holds some interesting points on how to gain more knowledge and how to use mathematical optimisation tools to analyse the effects of decision taking in favour of one or the other process option. This top-down orientated methodology shall be seen as a first step. The proof of a suitable as well as comprehensive set of indicators and aspects concerning the integrated sustainability assessment can be done with the help of multi-criteria mixed-integer optimisation methods. The evolution of the system over time, that is, the transition process, can be assessed using a system dynamics approach.

1.1 The Concept of Sustainability Indicators

Sustainability indicators consider all three dimensions of sustainability and do not focus on the environmental issues alone, although indicators have been widely employed for many years [3]. The first indicators were developed at the early 1970 by biologists to describe the health status of an ecosystem. As an early example, the study of Learner et al. [4] followed an approach to assess the environmental impact of pollution on fish and macro-invertebrates in a river. In 1972 the report "Limits to

Growth” of the Club of Rome pointed out that continued growth creates stress the boundaries of our system earth [5], which can be seen as a first step to think about sustainability. Nevertheless, the most common interpretations of sustainability nowadays are still based on the environmental aspects only. This has its origin partly in political debates starting in the late 80s and the resulting environmental regulations. Take the aspect climate change as an example: More or less, the whole discussion is on environmental issues and its effect on human kind. Nevertheless, this topic has the potential to include the social and economic dimensions as well by asking the questions how to pay for the changes as well as by whom, and what are the social consequence, if e.g. coastal areas are increasingly under the stress by flood and rising sea level.

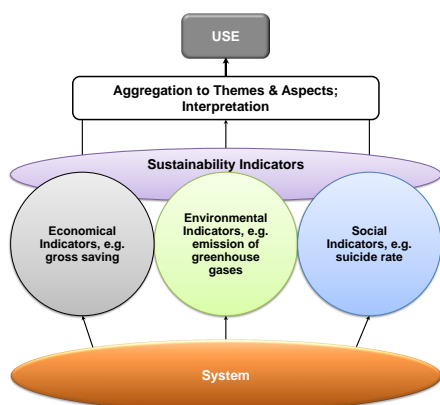


Figure 1: Description of the functionality of sustainability indicators.

As depicted in Figure 1, for a system analysis, the first step is the collection of relevant information and data, before the values can be interpreted. In the end, one should make reasonable use of the obtained results. The problem is, that there

are too many indicators to use them all at once without ballooning the costs 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 [6]. During the third revision by the Commission on Sustainable Development (CSD), the indicators were reduced to 96 with now only 14 themes or 44 sub-themes [7]. The German Strategy on Sustainability displays 21 themes associated with partly more than one indicator [8].

How many indicators for global sustainable value creation should be used and chosen? Simplifying the handling and maximising the outcome and relevance of information can be useful. One possibility is to group the indicators, as done e.g. by the United Nations with the proposal of three types of indicators: (i) driving force or pressure indicators, (ii) state indicators, and (iii) response indicators. The driving force indicators mark a process that influences a state indicator, which describes the conditions of a variable, whereas the response indicators gauge required progress in response of governments. Parris and Kates [9] 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:

- **What is to be sustained**

- *Nature*: (i) Earth, (ii) Biodiversity, (iii) Ecosystem

- *Life Support Systems*: (i) Ecosystem services, (ii) Resources, (iii) Environment
- *Community*: (i) Cultures, (ii) Groups, (iii) Places

- **What is to be developed**

- *People*: (i) Child survival, (ii) Life expectancy, (iii) Education, (iv) Equity, (v) Equal opportunity
- *Economy*: (i) Wealth, (ii) Productive sectors, (iii) Consumption
- *Society*: (i) Institutions, (ii) Social capital, (iii) States, (iv) Regions

All those aspects or themes and the partial look at them help to understand the complex concept of sustainability, to acknowledge the multiple and conflicting objectives to be sustained **and** developed, and to grasp the practical consequence of certain behaviours.

1.2 Use of Mathematical Modelling

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. In order to be able to achieve this goal, they developed the modern differential and integral calculus. One of the first applications of calculus to describe a non-physical but environmental problem was the predator-prey cycle model of Volterra [10] and Lotka [11]. This model was the birth of mathematical biology around the 1930s. It can not only be used to model a biological problem, but can also be applied in economical settings, for example the Goodwin model, to describe economical cycles of growth and de-

pression [12]. A prominent example for the analysis of economical and environmental resources is the World3 model developed by Meadows et al. [5]. These models are all numerically solved by simulation techniques, where the outcome of the model is determined by the given parameters and their functional relationships. In order to control such models, it is necessary to specify certain variables that allow a gradual change of the system's dynamic, and to introduce an objective function (or several objective functions, see the next paragraph). Then simulation techniques can no longer be applied, but methods from the field of optimal control and nonlinear optimisation, see [13], for instance.

Modern algorithmic approaches in multi-criteria (linear) optimisation are often based on variants of the Simplex Algorithm which was first presented by George Dantzig in 1947. During this time Dantzig was occupied with optimisation problems arising in military logistics. Linear programming plays an important role in modelling optimisation problems encountered in different scientific areas ever since [14].

The concept of efficient solutions commonly used in mathematics and computer science is synonym with the concept of Pareto optimal solutions. The latter is named in honour of Vilfredo Pareto who was an Italian economist, sociologist and engineer. The term of Pareto optimal solutions is commonly used in economics.

2 METHODOLOGY

2.1 Selection of Sustainability Aspects for Global Manufacturing

With the help of published sets of indicators and sustainability aspects, e.g. by the German Strategy on Sustainability or the CSD, it is possible to bridge the manufacturing network with the goal to identify, measure and create a set of indicators and aspects to represent the sustainable value creation process. The approach is twofold and will be applied in parallel.

First, a table with all the published sets of used indicators in the business surrounding is constructed. The description of the indicators helps to identify similar indicators, although the wording may be different, and use them on manufacturing processes. Therefore a matrix needs to be established with the relevant processes (production as well as management) in a vertical column and the indicators in a horizontal line. If the process can be measured with the indicator the intersection point will be marked. From that matrix a model can be derived to serve as a basis for mathematical optimisation. Within the model, the investigated parameters describe the interaction of the real system. Nevertheless, the indicators can usually be grouped or organised into sub-themes, which can be used for deriving a model as well, especially at this early stage of research. The sustainability aspect of climate change for example can not only be described by the indicator of greenhouse gas emission, but also by the change in average temperature, the rise of the sea level, the amount of rain, and others.

Second, a SD model according to sec-

tion 2.2.1 can be developed. The building blocks of the model will be equal to sustainability aspects which have been chosen at random at this early stage of research in order to check the way of thinking in the mathematical modelling of manufacturing processes in terms of achieving sustainable development. Later, the building blocks will represent real indicators by adopting this approach to a real case study, e.g. the production of a bamboo bicycle [15].

2.2 Mathematical Modelling

2.2.1 *System Dynamics and Optimisation*

We can think of indicators or aspects originating from the economy, the environment, or the society as complex entities, which form a finely balanced network of mutual dependencies together with their interrelations. Almost all indicators are influencing each other having either supporting or weakening effects. For the description of these relationships the “System Dynamics” (SD) approach provides the appropriate framework. SD was introduced by Jay Forrester in the 1950s to the 1970s [16, 17] 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” [18].

Deriving an SD model is a process that consists of multiple steps. The first step, however, is an oral description of the model’s scope. It is necessary to clearly define the application area of the model and, equally important, what the model should

not represent. Usually, models are not developed by a single person, but by a group instead. Hence a mutual agreement right from the beginning on the intended purpose and the goal needs to be achieved. During this process the basic entities (or aspects in our application) will be defined as building blocks of the SD model.

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 while changes to some other indicator occur. This yields a qualitative model of the system, showing its basic underlying structure. Usually 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. By studying the circles that are formed by some arrows one can already distinguish two types of loops. Reinforcing feedback loops have an even number of minus signs. They show that parts of the system are able to accelerate a dynamical trend. Counterwise, balancing feedback loops have an odd number of minus signs.

In a refined version of the causal loop diagram also numerical values are attached to the arrows, showing actually *how much* a certain indicator reacts depending on other indicators. This is a first step from a qualitative model towards a quantitative model that allows numerical simulations of its future behaviour using a linear pulse model: Starting from an initial state x_0 at time step 0, the next time step 1 can be deduced by evaluating the equation $x_1 = A \cdot x_0$. Here A is a square matrix with the aspects as rows and columns and the numerical arrow

values as entries, and x_0, x_1, \dots are vectors where each of their components represent one aspect. In general, the state in time $t + 1$ is obtained from the state in time t by $x_{t+1} = A \cdot x_t$. The trajectories x_0, x_1, \dots describe the future development of the system, as it is forecasted by the causal loop diagram in matrix A .

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 classical Runge-Kutta-method [13].

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.

Usually SD models are not only used to simulate the future development of a system, but also to influence the system by introducing certain policies. Such a policy can be an additional indicator with arrows connecting it with other existing ones, and a variable weight at these arrows. When setting these variables manually to certain fixed values, one can perform a simulation run for each setting. In this way it is possible to evaluate the outcome of the simulation and select a trajectory that seems favourable. The mathematical control problem for an SD model asks for the numerical computation of these policy variables that lead to a best possible (optimal)

trajectory, with respect to a given objective function.

2.2.2 Multi-Criteria Analysis

We consider the environmental, the economical and the social dimension which are taken into account in sustainable manufacturing as equally valued. Instead of preferring one over another, we want each indicator to be an independent objective function that needs to be optimised. However, in general, different sustainability indicators or aspects may be in conflict with each other and one cannot expect to find a solution that optimises all considered indicators simultaneously. Instead, one has to cope with trade-offs. For example, a manufacturing process that shows a better environmental performance (e.g. low amount of emissions damaging the environment or the human health) may probably not be very economical (higher investment and operation cost for additive technology, like filters or integrated technology, like closing material loops) or vice versa. A decision maker may be interested in a process whose performance for each indicator cannot be improved without a resulting trade-off in another indicator. This leads to the concept of efficiency and non-dominance, respectively. An efficient solution is a solution that cannot be improved in one objective without worsening another. In other words, considering an environmental, an economical and a social indicator as three different objective functions of a manufacturing process would be efficient if we cannot find another manufacturing process (producing the same goods) whose performance for each indicator is at least as good including a strict improvement in one of the indicators. The objective values of an efficient solution are

called non-dominated in the space of objectives. One of the goals in multi-criteria optimisation is to compute all non-dominated points and corresponding efficient solutions, respectively. A decision maker could then choose the most convenient solution out of this set.

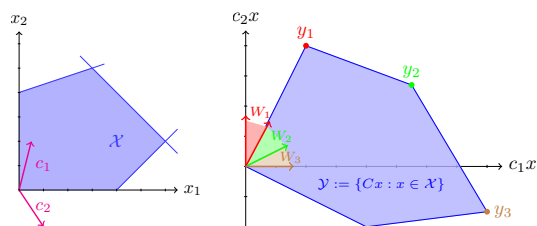
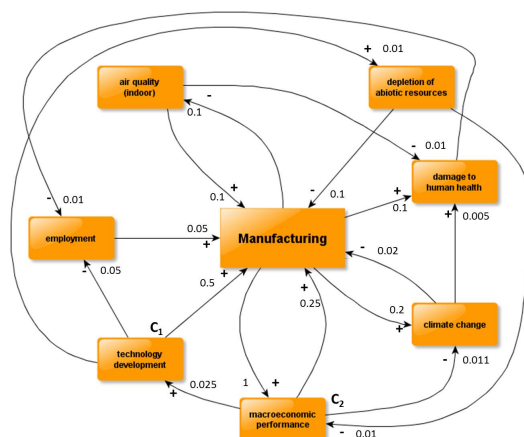


Figure 2: Solution space with two objective functions and corresponding objective space with three non-dominated points and corresponding weight space decomposition.

A well-known equivalence result states that optimising the weighted sum of the objectives $\lambda_1c_1 + \lambda_2c_2 + \lambda_3c_3$, where the λ_i are positive weights and the c_i are the considered objectives, yields an efficient solution. Furthermore, for each efficient solution one can find positive weights for which the weighted sum takes its optimum at the considered solution. Each non-dominated point corresponds to a set of weights which lead to this point in the weighted sum problem (see Figure 2). From an evaluation point of view, this weight space decomposition enables one to validate the objectives. In other words, the knowledge which weights and which weighted sum objectives, respectively, yield which non-dominated points qualifies the model builder to evaluate whether the used indicator values fall into place.

From an algorithmic point of view, the main incentive is the ability of a fast

computation of the set of non-dominated points. Due to the huge size of the latter that is still a challenging problem even for a small number of objectives.



3 DESCRIPTION OF A MODEL EXAMPLE

As outlined in Section 2.2.1 we start with a description of the scope of the model.

The model “manufacturing” should be able to derive a qualitative and justified statement of the development of a dynamic manufacturing process. The dynamic of the manufacturing process depends on the sustainability aspects, e.g. depletion of mineral resources, damage to human health, macroeconomic performance, etc. (see Figure 3). If the long-term behaviour of the model shows instabilities, the model should be able to point out possibilities for its stabilisation. It is not expected that the model returns a detailed description of necessary actions to be taken, but rather identifies hot-spots in order to look closer at the underlying indicators.

Figure 3: Causal loop diagram for the SD model “Manufacturing” in conjunction with costs as well as environmental and societal aspects.

The model shown in Figure 3 consists of the following sustainability aspects: depletion of abiotic resources, damage to human health, climate change, macroeconomic performance, technology development, employment, and air quality (indoor). The direction of the arcs show the influence direction as described below, whereas “+” stands for an increase and “-” stands for a decrease of the impact. The values at the arcs show the relative strength of a certain relation between the corresponding sustainability aspects. These aspects have the following qualitative interrelations:

- If *depletion of abiotic resources* increases, then manufacturing activity will decrease as well as the macroeconomic performance.
- If *manufacturing* increases, then the potential damage to human health will increase.
- If *damage to human health* increases, then employment will decrease.
- If *manufacturing* increases, then climate

change will increase, and this may result into a decrease of the manufacturing activity itself.

- If *climate change* increases, then this may lead to an increase of potential damage to human health.
- If *manufacturing* increases, then the macroeconomic performance will increase and as a reaction the manufacturing increases further.
- If *macroeconomic performance* increases, then the climate change will decrease, but the technology development will increase.
- If *technology development* increases, then manufacturing activity will benefit and increase, but there will be a decrease at the employment.
- If *employment* increases, then the manufacturing will increase.
- If *manufacturing* increases, then the air quality (indoor) will decrease.
- If *air quality (indoor)* increases, then the manufacturing activity increases as well.

A shift away from traditional manufacturing processes and consumption patterns is desired in order to adopt new – ideally sustainable – processes around the world and within the total value creation. For example, the raise of the macroeconomic performance by one unit due to an increase of the manufacturing activity could lead to the following two outcomes (see Figure 3). On the one hand, money from the GDP, as an indicator of the aspect ‘macroeconomic performance’, in a magnitude of 0.011 units should be used to compensate the social cost related to carbon [19]. Using these numbers we are able to set up a linear pulse model and perform a dynamic simulation, as outlined in Section 2.2.1.

Moreover, it is possible to give an ordering of the elements according to their

passive, active, critical and buffering capabilities within the system (see Vester, 2007 [20]). This is done by the analysis of the active and passive sum (row and column sums in matrix A , respectively). Then the following information is obtained from the model’s data:

- most active element (affects others, but not strongly influenced by others): **technology development**;
- most passive element (strongly influenced by others, but little effect on others): **damage to human health**;
- most critical element (affects others and influenced by others): **manufacturing**;
- most buffering element (little effect on others and little influence from others): **depletion of abiotic resources**;

If the system is in a critical unstable state (in whatever sense), then the influence of an arc such as “technology development \rightarrow Manufacturing”, between the most active and the most critical element, is crucial. Hence we will later study the dynamic behaviour depending on this value, which we denote by C_1 in Figure 3.

Since we want to take control of the climate change, we additionally identify the arc “macroeconomic performance \rightarrow climate change” as important, and analyse the dynamic behaviour of the model depending on this arc weight denoted by C_2 .

4 RESULTS & DISCUSSION

The linear pulse model described in Section 3 is simulated to forecast the influence of a single-unit increase of manufacturing at time t_0 on all the other sustainability aspects. This increase can be related to a political desired stimulation of the economy,

and can therefore help to understand the effect of such short term measure in the long run.

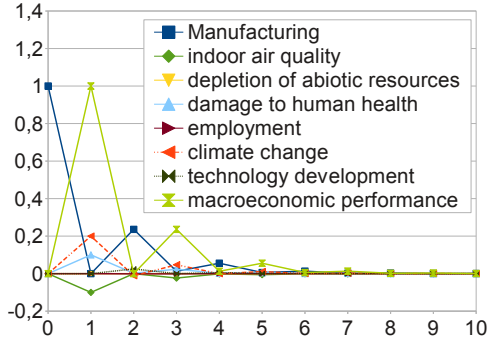


Figure 4: Results from the SD model “Manufacturing” for all aspects, un-scaled.

The arc values shown in Figure 3 cause the system to reach a steady state within a reasonable period of time, which means that the effect of single stimulation of the manufacturing activity (by one unit) fades off after only a very few time steps (Figure 4). If all arc values are scaled by a large positive constant factor, then a single pulse will be self-energising and the whole system diverges. Thus it is possible to identify the tipping point between a complete absorption of the start impulse and a diverging system. This threshold level at which the system changes from one to the other states lies at approximately 1.95. What does that mean? If influences of the sustainability aspects are as given or at most (roughly) two times higher, then the system will still be able to reach a steady state condition. This steady state corresponds to a higher level of manufacturing, but also to a higher level of climate change, as the simulation results indicate. If the scaling parameter becomes greater, the system does not reach

a steady state any more, compare Figure 4 and Figure 5. At this point a self-energising effect becomes visible and e.g. manufacturing keeps growing at an exponential growth rate, but also climate change as well.

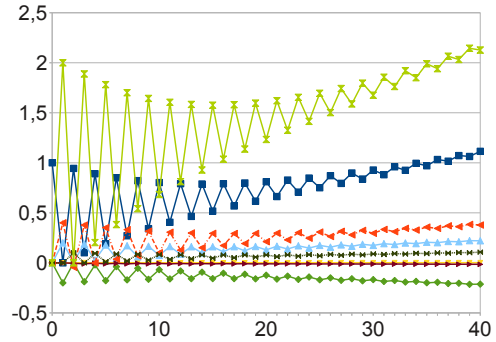


Figure 5: Results from the SD model “Manufacturing” for all aspects, scaled with a factor of 2 (legend see Figure 4).

Being at the system’s tipping point, it becomes interesting to analyse the dynamical behaviour of the system depending on the arc values of those arcs in Figure 3 denoted by C_1 and C_2 . When varying the values at these arcs the simulation will respond immediately to even small changes. From the change in the trajectories of the sustainability aspects it is then possible to deduce measures for a strategic control of the modelled system.

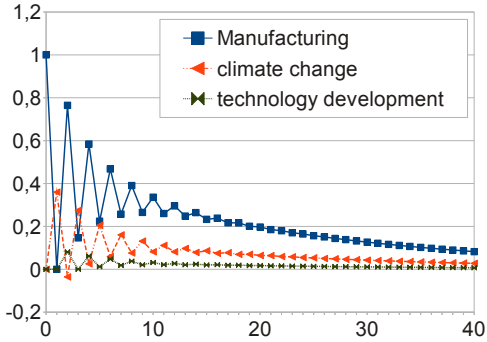


Figure 6: Results from the SD model “Manufacturing” for the aspects climate change and technology development, scaled with a factor of 1.8, C_1 set to 1.

The values of arcs connecting to the active and critical elements are then varied in order to simulate their influence on the system. By setting the scaling factor to 1.8 near the tipping point, a change of the variable C_1 to 1 leads to no significant effect (Figure 6), but with a scaling factor of 2 and a change of $C_1 = 1$, the manufacturing activity grows much faster (compare Figure 5 with Figure 7). The initial idea of increasing technology development especially to enhance manufacturing activity is clearly visible. However, the environmental burden, here climate change, is also increasing at the same time, which should be avoided by means of sustainable development. Therefore, the variable C_2 has to be adopted. By setting $C_2 = -0.103$ the aspect “climate change” reaches a steady state. This means an increase of the GDP drawing by the factor of approximately 10 to -0.103 units from the macroeconomic performance is needed to pay for compensation action concerning climate change (Figure 8) and still have an increase of manufacturing.

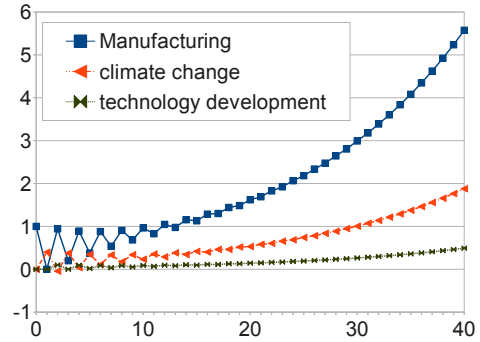


Figure 7: Results from the SD model “Manufacturing” for the aspects climate change and technology development, scaled with a factor of 2 and $C_1 = 1$.

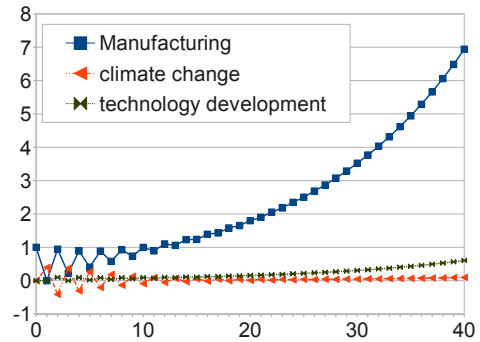


Figure 8: Results from the SD model “Manufacturing” for the aspects climate change and technology development, scaled with a factor of 2, C_1 set to 1, C_2 set to -0.103 .

5 CONCLUSION & OUTLOOK

This paper has shown that the dynamic simulation of a complex model like the one used in this study is possible and leads to

reasonable results. Nevertheless, this theoretical approach has to be validated with a case study in the upcoming period. Therefore, the demonstrator (Life Cycle of a bamboo bike) by Schau et al. [15] will be used to do so.

An idealistic long-term goal is the combination of the system dynamics approach with multi-criteria optimisation. Each resulting trajectory from the system dynamics approach can be considered as an objective which needs to be optimised. Considering a certain function that can be evaluated for each trajectory (e.g. an integral function evaluating the surface area under the plotted graph) yields different objective values for each considered trajectory. Meanwhile, finding the trajectories which are efficient for a given function leads to a multi-criteria optimisation problem.

ACKNOWLEDGEMENT

We gratefully acknowledge the funding of this work by the German Research Association (Deutsche Forschungsgemeinschaft, DFG), Collaborative Research Center CRC1026 (Sonderforschungsbereich SFB1026).

References

- [1] Finkbeiner, M., Schau, E., Lehmann, A., Traverso, M., 2010. Towards Life Cycle Sustainability Assessment. *Sustainability*, 2:3309–3322.
- [2] Seliger, G., 2007. *Sustainability in Manufacturing*. Springer, Berlin, Heidelberg, New York.
- [3] Bell, S., Morse, S., 2010. Sustainability Indicators: Measuring the Immeasurable? earthscan, London, Washington D.C., 2, revised edition edition.
- [4] Learner, M., Williams, R., Harcup, M., Hughes, B., 1971. A survey of the macro-fauna of the river Cynon, a polluted tributary of the river Taff (South Wales). *Freshwater Biology*, 1:339–367.
- [5] Meadows, D., Meadows, D., Randers, J., Behrens III, W., 1972. *The Limits to Growth*. Universe Books, New York, NY.
- [6] UN-DESA, 2001. *Indicators of Sustainable Development: Guidelines and Methodologies*. Technical Report, United Nations.
- [7] UN-DESA, 2007. *Indicators of Sustainable Development: Guidelines and Methodologies*. Technical Report, United Nations.
- [8] Bundesregierung, 2012. *Nationale Nachhaltigkeitsstrategie - Fortschrittsbericht 2012*. Technical Report, BMU.
- [9] Parris, T. M., 2003. Characterisation and Measuring Sustainable Development. *Ann. Rev. Environ. Resour.*, 28:559–586.
- [10] Volterra, V., 1926. *Variazioni e fluttuazioni del numero d'individui in specie animali conviventi*. Memorie della Regia Accademia Nazionale dei Lincei. Ser. VI, 2:31 – 113.
- [11] Lotka, A. J., 1925. *Elements of Physical Biology*. Williams and Wilkins Company.
- [12] Goodwin, R. M., 1967. A Growth Cycle. In C. H. Feinstein, editor,

- Socialism, Capitalism and Economic Growth. Essays presented to Maurice Dobb. Cambridge University Press, Cambridge, 54 – 58.
- [13] Betts, J. T., 2009. Practical Methods for Optimal Control and Estimation Using Nonlinear Programming. SIAM Advances in Design and Control, The Society for Industrial and Applied Mathematics, Philadelphia, PA, USA.
- [14] Dantzig, G., 1963. Linear programming and extensions. Princeton University Press and RAND Corporation.
- [15] Schau, E. M., Chang, Y.-J., Finkbeiner, M., 2012. Manufactured products & how can their life cycle sustainability be measured? A case study of a bamboo bicycle. In The 10th Global Conference on Sustainable Manufacturing. Accepted.
- [16] Forrester, J., 1961. Industrial Dynamics. Waltham, MA, Pegasus Communications.
- [17] Forrester, J., 1969. Urban Dynamics. Waltham, MA, Pegasus Communications.
- [18] Forrester, J., 1973. World Dynamics. Waltham, MA, Pegasus Communications.
- [19] Greenspan Bell, R., Callan, D., 2011. More than Meets the Eye - The Social Cost of Carbon in U.S. Climate Policy. In Policy Brief. World Resource Institute, 1–16.
- [20] Vester, F., 2007. Die Kunst vernetzt zu denken. dtv.