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ACHIEVING SUSTAINABILITY THROUGH A COMBINATION OF LCA AND DES INTEGRATED IN A SIMULATION SOFTWARE FOR PRODUCTION PROCESSES

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ABSTRACT

This paper outlines the application of a special Environmental Management Information System (EMIS) that combines discrete event simulation (DES) and life cycle analysis (LCA) in addition to material flow analysis as an integrated part of the simulation software. The motivation behind the combination of these different techniques is to close the gap between identifying only parts of the life cycle, namely production processes, when simulating such processes, while at the same time focusing more sharply on LCA allowing for the resolution of results by DES and the detailed view of what is or might be happening in the production phase of the cycle. This view focuses not only on economic optimization but also on material flow analysis with a possible integration of social criteria opening the door to sustainable production in reality in the future. The paper will highlight important development phases as well as current applications of the software.

1 MOTIVATION AND INTRODUCTION

This chapter will briefly set out our motivation for developing and concentrating continuously on the development of the simulation software that forms the basis of this contribution. It will also introduce the approach to it and its development by placing it in a chronological context and providing an outline for the following sections.

1.1 Motivation

The basis of our motivation is the understanding that current consumption patterns and the resulting extraction of global resources are increasingly endangering the *"life-sustaining services of the earth"* (WRF 2008; Hilty and Ruddy 2010) and this while the *"attraction of the western style of life"* and its resulting problems still has a high *"global attraction potential"* (von Lucke 2011). Following that conviction, dematerialization and higher resource efficiency become mandatory concepts for the future to prevent ecological and resulting social disruption (see Widok, Wohlgemuth and Page 2011 for more details). This ultimately implies that more companies, especially in the production sector, need to strengthen their environmental and social efforts.

Proceeding from a system-thinking orientation, if we consider one of those companies as a minimal representation of an economy, we conclude that if it has a purely economic orientation it will not lead and contribute to sustainable growth. A strong social commitment or intensive environmental management and resulting measures, however, will also not have any positive effects if the company structure and operations cannot bear the load they place on it. Thus it is imperative that these three characteristics of sustainability are combined by means of balanced efforts leading to a synergistic increase in value (Stahlmann 2008; Schmidt-Bleek 2008; von Pappenheim 2009). For that, however, it is imperative to learn more about the interaction between the three perspectives and to render it possible to actually compare the consequences of operational measures acknowledging the three different aspects while paying tribute to the system as a whole.

In that regard it has always been our goal to use simulation techniques to analyze processes and, more specifically, production processes to find not only weaknesses in an economic optimization but also by combining material flow analysis (MFA) and discrete event simulation (DES) especially in the environmental aspect.

The industrial revolution in the 19th century led to a rise in labor productivity by a coefficient of 20; today the factor of labor is not small compared to the one of resource-productivity which failed to evolve in quite the same manner (von Weizäcker 2011). Following that thought and realizing that from a *natural science perspective* (Hilty and Ruddy 2010) the only possible way to maintain a similar standard of living, without drastically changing our economies and paying attention to vanishing resources, would be to increase resource efficiency in a similar manner to that applied to labor productivity in the past. Subsequently, we developed numerous software tools over the last decade that integrate different depths of sustainability simulation and which focus in particular on resource efficiency; one of them will be introduced in the following.

1.2 Introduction

In the Proceedings of the Winter Simulation Conference in 2009 we presented one of the first applications of the Material Flow Simulator MILAN, a concept that was first presented in 2006 (Wohlgemuth, Page, and Kreutzer 2006) and refers back to the concept of combining MFA with DES from 2005 (Wohlgemuth 2005).

Since then we intensified our work on various levels of the architecture and extensions of the simulation engine as was shown in different publications (see for example Panic, Schnackenbeck, Wohlgemuth 2008; Jahr et al. 2009; Jahr, Schiemann, Wohlgemuth 2010, Widok and Wohlgemuth 2011) and will be elucidated more thoroughly under Section 3.

In the Proceedings of the Winter Simulation Conference in 2011 we presented a new, broader approach incorporating the latest sustainability research (Widok, Wohlgemuth and Page 2011) and new technologies (cf. Jahr et al. 2009) to not only pay tribute to the complexity of the concept of sustainability but also to incorporate new technological developments as we concluded our prototype. It was understood, that the usage of DES and MFA was not yet sufficient to really reflect intelligent decision support considering an sustainability optimization, because on the one hand MFA did account for environmental aspects but not for social ones, also considering LCA our focus was still limited to the production phase, which in some cases makes only for a small impact when one wants to consider the environmental and social overall quality of a product.

Hence, a year later, we are intensifying our focus on the potential of the software for environmental reporting by adding life cycle assessment (LCA) functionalities, while putting it through the next iteration of use cases in the research project EcoFactory with different industry partners from Switzerland and the methodical help of two research partners: the Swiss Federal Laboratories for Materials Science and Technology (EMPA), which provides a lot of experience in the integration and usage of LCA and the BWI/ETH Zürich which provided the contacts to the Swiss industries and is leading the industrial economical part of the project (see acknowledgements).

To clarify why this next step has been taken and how the different perspectives are combined in a simultaneous approach, the next section will concentrate on our methodical approach, while section 3 will present the current status of our development, before section 4 will conclude this contribution with an outlook.

2 SUSTAINABILITY AND SIMULATION – OUR APPROACH

2.1 Capital based Approach to assessing Sustainability

In 2011 we elaborated the normative nature when trying to derive an applicable strategy for the assessment of the sustainability of measures (cp. Widok, Wohlgemuth and Page 2011).

We there defined sustainability mainly as the agglomeration of actions/campaigns/processes that have a positive effect on the regeneration of social, environmental and/or economic capital on the one hand, and/or reduce the degradation of this capital on the other, bearing in mind that protection/growth of that capital would be the normative goal in this case (see also Figure 1).

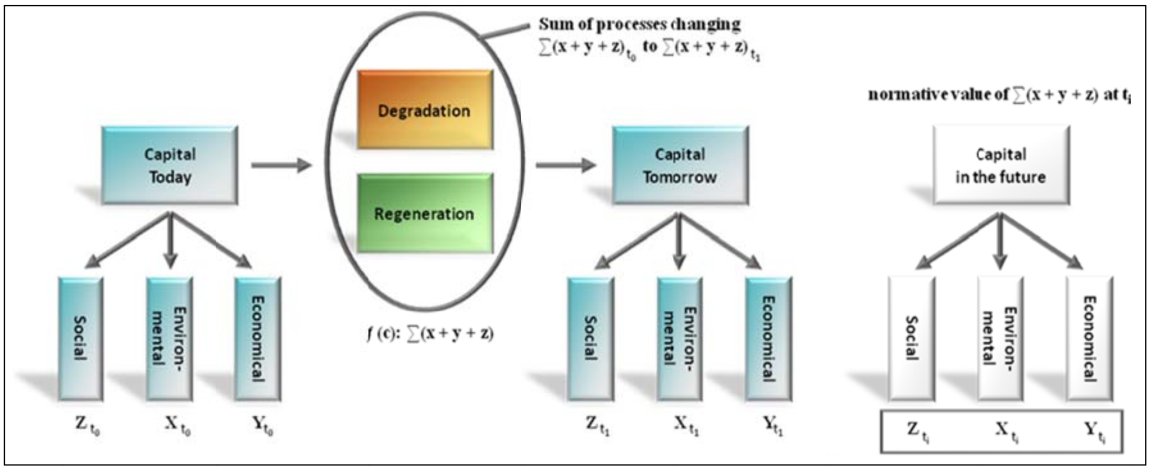

Figure 1: Capital Approach - Sustainability (Widok, Wohlgemuth and Page 2011)

Our focus remains on the question of how to guarantee comparability between the different consequences from the economic, environmental and social perspective, to actually achieve a balance in growth where growth is the normative goal or respective reduction/equilibrium where one of these would be the goal. This so called balance is what sustainability theorists have been trying to define, and have thus struggled with, from the very outset. Throughout sustainability theory, from (Meadows 1972), (Lynam, Herdt 1989) and (Pezzey 1992) – who already listed 27 different definitions for sustainability – (Pretty 1995) up to (Bell and Morse 2008), the question of the objective that had to be protected/balanced (in our case named capital in the forms of social/environmental/economical capital) was addressed. Furthermore, there was a broad understanding that shrinking processes can also be considered sustainable. In addition, Pezzey already noticed that the normative value is logically shifting and thus the assessment or comparison/normative value must shift with it – or in other words – the assessment must be iterative, while the same measure can be deemed very sustainable in one iteration and very unsustainable in the next. Pezzey even argued that it makes the final definition of sustainability impossible, while we argue that by using normative values, which indeed must have a timestamp, it is possible to classify sustainable and unsustainable measures/behavior.

As we also realize that the definition of sustainability indicators is the critical part of this method of assessing sustainability, the definition, in conjunction with the intended usage in simulation experiments, allows a variety of approaches to be tested when assessing the sustainability-enhancing potential of measures. It is thus more operational than trying to find a questionable solving formula for what can be considered sustainable at any moment in time.

The assessment of sustainability in iterations is also very compatible with simulations, as experimenting naturally comes down to repeating a scenario (experiment) with different sets of input values and comparing the results, in order to conclude which input values are the best set to achieve a normative goal. Simulation can thus be used to show the possible effects of alternative conditions and courses of action. It is mainly used when the real system cannot be tampered with, because it may not be accessible, or it may be dangerous or unacceptable to engage it, or it is being designed but not yet built, or it may simply not exist (Sokolowski and Banks 2009).

In that regard simulations are perfect tools when it comes to experimenting with uncertain outcomes, which may be harmful or contra-productive. When assessing possible changes due to restructuring measures in the industry, it is a logical consequence that these changes would be simulated before implementing them. Another reason for the usage of simulation is the impossibility of using mathematical/analytic optimization methods, once the number of uncertainties and thus variables becomes too great to achieve results in a reasonable amount of time/costs, which is usually the case in our intended studies.

While simulations and more specific DES have already been used for a long time to hint at optimizations for production systems, combining them with MFA in one model was only realized recently (Wohlgemuth 2005), the reasons behind this solution will be explained in the following.

2.2 Benefits of combining DES and MFA

The combination of DES and MFA in one software was the result of an understanding process, that both approaches had been used for a while in producing companies, though operating on different ends for different means and usually operated by different people but using a similar set of data and overlapping goals because the reduction of material naturally also resulted in greater cost effectiveness.

So based on the attempt to combine the economic perspective with goals such as short throughput time, adherence to schedules, high workload, low stocks and the environmental perspective with goals such as high material efficiency and hence greener products, we focused on the process sequence. There we realized that the same points in time could be found for modeling a DES model as well as for a Material Flow Simulation model, hence the idea of combining both models was born and subsequently implemented over the last decade (see also Figure 2).

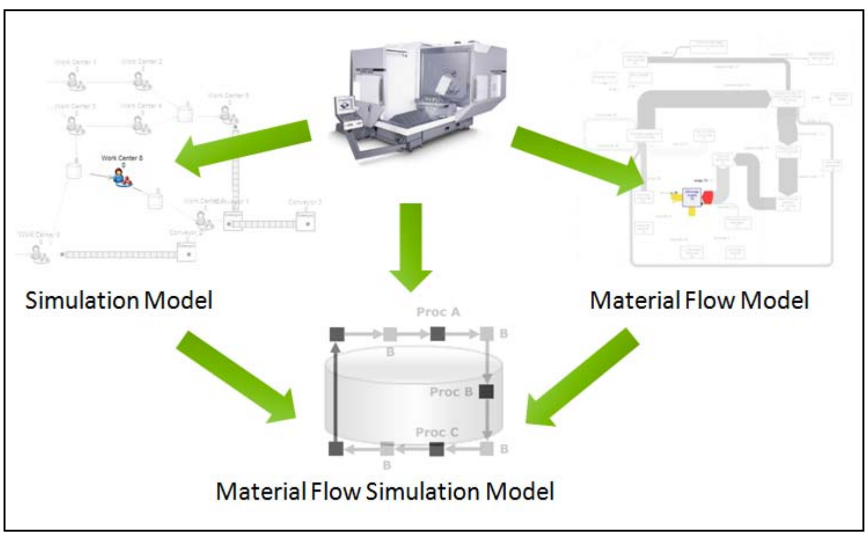

Figure 2: Combination of models

The main benefits of this combination can be summarized as follows:

- Analysis of environmental impacts of economic changes and vice versa
- Simultaneous approach
- Only one model to create
- Single software solution

2.3 Benefits of combining DES/MFA with LCA

The idea of enhancing our prototype by combining it with LCA data came as a result of various projects in the LCA sector (see Reinhard et al. 2011 for example) and the object to broaden our view even further away from concentrating solely on the production phase of a product to incorporate even more data including the impact of the used materials and how those came to the point in time when they entered our simulation experiments (see Figure 3).

While that purpose was naturally intended from the beginning, the data for considering a broader view has made substantial progress in resolution and quality over the last decade and thus becomes increasingly operational for consideration in decision making.

Especially when attempting to introduce social criteria, data that was previously unconsidered, such as the country of origin of a material and the manner in which it was produced (for example through child labor) could now be taken into account and thus enable a much more realistic perception of the sustainability of a product created which remains the long-term goal of our simulation software.

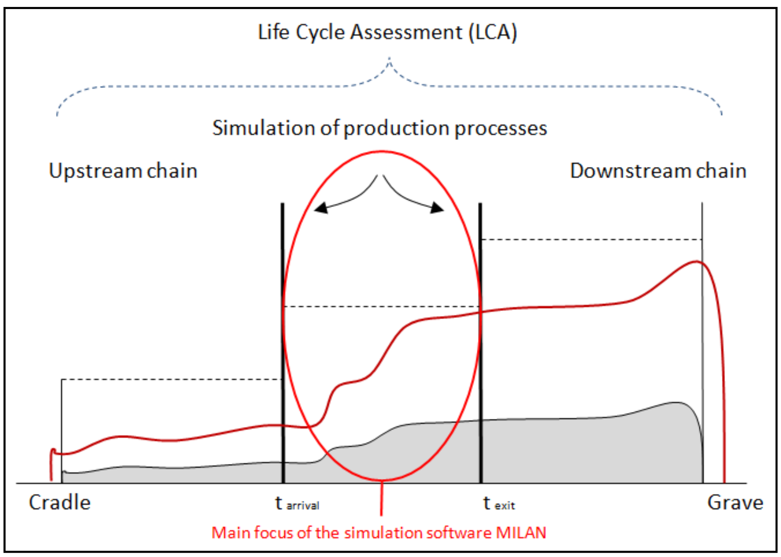

Figure 3: Focus of the simulation software MILAN considering the life cycle

2.4 Benefits of combining LCA with DES/MFA

Looking at it from the other angle, namely the benefits of using DES and MFA in addition to existing schemes of LCA, one has to take a look at what LCA data usually provides as result.

For example, the Global Warming Potential indicator (GWP) integrates different gases (CH4, N2O, etc.) and resolves them in one single number by multiplying it with the respective masses of the gases ($GWP = \Sigma_i GWP_i \bullet m_i$) resulting in a CO2 equivalent.

A similar, mainly output-oriented, methodology would be the “Umweltbelastungspunkte” (UBP) which considers the mass of interferences in the ecosystem by emitted substance (UBP/g), energetic resource (UBP/MJ), or even land use (UBP/m^2 land use) and then integrates those as well by multiplying them with a previous defined ecological interference factor, in both cases the result is a single number.

While we have the highest regard for the parties involved in working on these solutions, and we use both standards in our implementation and so acknowledge its usefulness, still logically one has to question the sharpness of a single number reflecting the disruptive potential of a product over its whole life cycle.

The combination with DES and MFA thus allows for a more precise look at the production phase of the life cycle and enables variation of the input values with resulting effects on the values mentioned

(GWP, UBP). The main benefit of the integration is therefore the higher resolution and, by experimenting (Figure 4), the possibility to adhere to different scenarios and consider their impact on the whole life cycle or rather its respective evaluation.

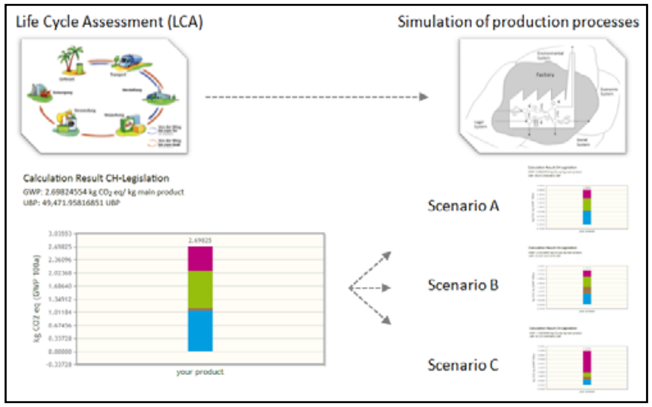

Figure 4: Experimentation resulting in different LCA results

3 DEVELOPMENT OF THE SIMULATION SOFTWARE MILAN

3.1 Early Development Phases

In 2005 the importance of the instruments for modeling and simulation were already well established for usage in the analysis and planning of complex systems in many domains (see Page and Kreutzer 2005 for examples).

Discrete event simulations are a powerful method to represent production processes close to reality and to follow time intervals of different sizes from a few hours up to several business years for investigating aspects depicted in the introduction.

The adaptation for usage in light of our primary focus – resource efficiency – was carried out around the year 2000, when the proposal was made to use simulation techniques for supporting the application of the Material Flow Network method (Wohlgemuth, Bruns and Page 2001) (Wohlgemuth 2005). Material Flow Networks were developed at the University of Hamburg (Möller 2000) and are based on the Petri-Net theory. By these means, simulations can be used to calculate unknown environmental quantities, such as determination of the necessary load of connected input flows considering complex systems (see Joschko, Page and Wohlgemuth 2009). Furthermore in Material Flow Networks, information is rarely linked to objects like products or process steps which follows the principle of hiding non-relevant data considering the simulation.

The prototype discussed in the following resulted from a variety of research during the years 2000 up to today. While on one hand, its discrete event simulation components allow an accurate analysis of typically economic aspects and industry related aspects, on the other hand, its material flow analysis components added an environmental perspective to the discrete event simulation model for the first time, i.e. a consideration of relevant material flows and transformations such as:

- consumption of commodities, resources and additives;
- energy demand;
- waste accumulation;
- emission generation.

Various publications already hinted at the potential of the software. Although we presented the first application of the Material Flow Simulator Milan in 2006 (Wohlgemuth, Page and Kreutzer 2006), we then made several technological changes: reprogramming the software using newest technologies (Panic, Schnackenbeck, Wohlgemuth 2008) (Wohlgemuth, Schnackenbeck, Panic, Barling, R.-L. 2008).

The intensified work on different levels of the architecture and extensions of the simulation engine resulted in a powerful simulation tool that is currently working in different use cases in the industry. Since 2009 we are also trying to find ways to go beyond the material flow perception and broaden the view, through LCA and other methodologies to get even closer to assessing the sustainability of the production phase and or products themselves.

3.2 The Development of MILAN

The first implementation of MILAN was realized using the Delphi version of DESMO-J, called DESMO-D, the framework and components in high level language Delphi. The component-based architecture was realized using COM-Technology (Wohlgemuth, Page and Kreutzer 2006). This realization, however, seemed outdated and has been renewed since 2009 and MILAN has been re-implemented.

The new development of the material flow simulator MILAN is based on the open-source plugin framework EMPINIA (http://www.empinia.org) (comparable to the Java framework Eclipse (http://www.eclipse.org)).

EMPINIA, which was developed in the course of the EMPORER project, is designed for the development of complex domain-specific applications especially in the field of environmental management information systems (EMIS) (Wohlgemuth, Schnackenbeck, Panic and Barling 2008). It is a component-orientated extensible application framework based on Microsoft's .NET (http://msdn.microsoft.com/de-de/netframe-work/default.aspx) technology with the purpose of supporting and simplifying the development of complex software systems (see Figure 5).

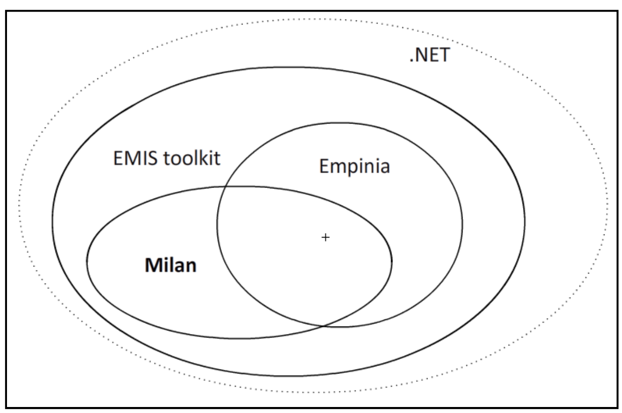

Figure 5: Classification of the development environment EMPINIA and the software MILAN

For MILAN it was necessary to provide libraries of simulation components (e.g. for production systems: machines, transporters, system boundaries) which enable the modeler to represent and simulate his system adequately. These components can be added to an application i.e. as building blocks via a plugin mechanism and can thus be used to build a user-specific model.

Natural variations such as varying inter-mediate arrival times of production jobs can be represented by generating pseudo-random numbers following given stochastic distributions. The simulation components naturally also have access to many stochastic distributions (e.g. Normal, Bernoulli, etc.). They are used to generate streams of random numbers, for example to schedule an event, which follows a certain arrival probability. In addition to these existing distributions, user-defined distributions can also be added via plugins.

This implementation may lead to an easy development of user-specific components with low dependencies and an attachment to a modeling tool box for a certain application field which is not possible with other simulation tools (already described in Page, Lecher, Claasen 2000) (Page Kreutzer 2005). These components can either be generally applicable or might be used for very specialized purpose. Specialized entities are developed for a whole production sector (e.g. semi-conductor sector with coater, stepper and dispatcher) (Wohlgemuth, Page, Mäusbacher, and Staudt-Fischbach 2004) (Wohlgemuth 2005) or they represent a production component of a certain company with its specific parameters. In contrast, general components are highly abstracted and are applicable to many production systems (Jahr, Schiemann and Wohlgemuth 2009). The goal of this project was the development and implementation of such general entities for MILAN.

Another important gain resulting from the EMPORER research project was the implementation of very abstract simulation entities for the analysis of production systems. These entities enable users to model and simulate a broad set of production systems. Due to their modularity and the plugin mechanisms of EMPINIA it is very easy to add more specialized entities to the production system's domain and to use them for a material flow simulation.

After that the production components were verified by performing a simulation study in a company that produces solar panels. The problems, results and experiences of this validation were used to improve and enhance the components, the simulation infrastructure and MILAN itself as a simulation tool.

Besides the components which come with EMPINIA, there are many plugins taken from a designed EMIS toolbox which were then combined with MILAN. The simulation capabilities of the MILAN software consist of the simulation core, a bundle for discrete event simulation and simulation components.

The simulation core consists of the central simulation service, interfaces and abstract base classes for models, experiments and model entities. These are used in each kind of simulation. The simulation service provides models and experiments in a way that other software parts can use them. The simulation core gives models and their entities access to the functionality of a domain model service. A domain model defines the domain of an EMPINIA-based application, its elements and their relations as well as rules that apply to this domain. MILAN consists of the domain 'simulation' with elements like 'model' and 'entity'. Among other important functionalities, the domain service provides opportunities to retain its elements. That is the reason why this service is used in MILAN to save and load previously created models.

A bundle for discrete event simulation extends the simulation core with classes specific to the discrete event simulation approach. These classes use an EMPINIA extension that enables the development of logical graphs in order to combine entities of a model into a network diagram. The basic generic experiment component is extended with an event list and a scheduler which are used to simulate time in discrete steps.

3.3 Features of MILAN

The common features of the MILAN software will be summarized below.

Execution of a material flow simulation requires the creation of a model that represents the system under investigation. Up to now this has required two models, one for the material flow analysis and another one for the simulation-related aspects. The material flow simulator MILAN, however, is able to integrate both specific views into one model. It retains the common model structures and adds the different sets of parameters. These parameters, such as sets for material accounting or probability distribution streams, can be added subsequently to the model structure.

The modeling is done using a graphical network consisting of nodes and edges and hence reflecting the origin, i.e. the Petri-Net Theory. The nodes describe important model elements where products are handled or stay for processing for a certain period of time. Edges work as logical connections between these elements and are also intended to show the process flow direction.

Manipulating model parameters for the simulation and material flow perspective is done by means of property editors enabling a simple and consistent way of setting values for all types of properties. are Standard editors are implemented for the production system domain. These allow changes to component-specific parameters, such as setting distributions, accounting rules, queue lengths or capacities etc.

The graphical manipulation of building blocks leads to a faster development of a model. The graph editor can be used to manipulate and create models. The editor itself can work in different domains. Domain specific functionality and the graphical representation have to be defined by plugin developers enabling the editor to handle new domains and their components which also use plugin definitions.

No analysis can be done without results. These are shown in reports which can be designed with the help of the reporting system. The data for the reports is aggregated during simulation runs by a system of observers that listen to changes in the material accounting and simulation entities.

3.4 Recent Developments

The development of new features and testing of the full capacity of MILAN's functionality are ongoing. Combining economic and ecological indicators in one model has already been achieved. The research work and development of MILAN will be continued professionally in the new founded German startup geWISSEN. So we can guarantee better support and further professional development for MILAN to potential customers. In the following chapter, we will outline visions as to how MILAN might get even closer to a sustainability-enhancing simulation system.

As mentioned in the introduction, the latest change to the software has been the integration of LCA data in the course of the EcoFactory project. This was done in cooperation with EMPA and the EcoInvent-Data (http://www.ecoinvent.ch) provided. Several use cases are currently underway in the Swiss industry (http://ecofactory.f2.htw-berlin.de) and (http://www.lim.ethz.ch/forschung/projekte/ecofactory). These use cases focus on different branches of business to allow for thorough testing of the application and proof of concept. Results will be presented in the conference.

Furthermore there is constant work on optimizing the graphical user interface (GUI), as this is one of the critical parts considering the acceptance and usage of software today. One has to acknowledge that very specific software that is often only usable by experts, due to the high level of sophistication of functions and product features, often leads to users switching to simpler software solutions, even if those disregard functionalities. Optimizing the GUI hence remains one primary focus of development.

We also worked on combining our prototype with tools that we developed for mobile data acquisition, the goal here is that the sometimes longer and annoying process of entering system values could be switched to the usage of phones and tablets, which would then be at work within the factory itself and transmit the data in an XML format for the usage in the tool. This also resulted in the automatic validation of input values, through the comparison with older data sets and known parameters. The thread of making mistakes by putting in wrong values into the system is hence reduced.

4 OUTLOOK AND CONCLUSION

4.1 Conclusion

The full potential of the software MILAN remains still to be seen, as the results of this iteration of tests in the industry has not yet been completed. First results show promise however. It is our believe that the combination of different methodical approaches such as DES, MFA and LCA will pay out in the long run and will even be further developed; the sharpness of LCA furthermore upgraded by possibly simulating not only the production phase of the cycles but account for other eventualities in other phases as well using simulation software. LCA on the other hand allows for another way of integration also social criteria; in the future it will be a great challenge considering how the quality of decision can be characterized considering the three different pillars of sustainability, which is also why we have intensified our research in that direction. It becomes easier to actually predict outcome considering the pillars, for example scenario A would result in 20% less used resource, 10% higher financial outcome and scenario B for 15% less used resource and 2% higher financial outcome – now if one takes into account a primary normative goal, a qualification of these scenarios seems easy, its either the one of the other, but reality is usually not that simple, especially when we consider not only the economical and environmental outcome but the social outcome as well. It is in that regard that one of our major research fields at this moment is finding ways on how to guarantee comparability of possible simulation results.

4.2 Outlook

In that regard focus on the social pillar of sustainability was strengthen during the last year and while new components for specific application areas are still under development the main functionalities becoming more and more solid, which results in a higher focus on making them more usable and ensuring the acceptance of the software. It remains to be seen if the combination and usage on mobile platforms can improve this aspect in the coming year.

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