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Abstract: Sustainability impact assessment (SIA) studies how factors such as policy, management or technology development affect the sustainability of a sector or a chain of value adding processes and helps decision-makers to assess impacts of decision alternatives. The Tool for Sustainability Impact Assessment (ToSIA) was developed as a transparent platform for assessing the sustainability impacts of changes in Forest Wood Chains (FWC). The adopted approach is flexible and can thus be applied to other similar domains and the scope of analysis can be defined by the user. Target users of the tool and its assessments include scientists, consultants and policy makers. ToSIA implements SIA by calculating material flows of an interlinked sequence of processes and combining each process' volume with indicators of environmental, social, and economic sustainability, which can then be aggregated for process groups or the whole FWC. The results are compared to other results derived with alternative assumptions, which produce changes in sustainability indicator values. A change in an indicator result in response to a changed external driver is a quantified impact. Alternatives bring out quantitative differences (impacts) of changing between efficiencies of technologies or of redistributing resources between alternative/competing uses. This paper presents how ToSIA has been implemented from a modeling and software viewpoint. There is a special focus on describing the utilization of the Open Modeling Interface (OpenMI) Standard for ToSIA material flow calculation. The inherent cyclic nature of FWC flows (recycling) is a special issue that was addressed by performing iterations of calculation of carefully specified material flow loops, implemented through the calculation of a diminishing mathematical series. Examples from case studies are used to demonstrate the utilized approach in practice. The future development prospects of the modeling aspect of ToSIA are also discussed.

***Keywords**:* Sustainability; Impact Assessment; OpenMI; ToSIA; Indicators

1 INTRODUCTION

The prevalent definition of sustainability or sustainable development was given by the Brundtland commission as "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [WCED, 1987]. Sustainable use of natural resources is nowadays accepted as a worthy societal ambition. It is self-evident that continued consumption of a limited resource at a higher pace than its regeneration or recycling will lead to the depletion of that resource. The concept of eco-efficiency is roughly equivalent to producing more products or services with less resources, waste and pollution. The European Commission established improved resource-efficiency and eco-innovation as important targets for developing a green economy [European Commission, 2011]. The sustainability concept is not constrained to just resource use efficiency, it can be viewed in terms of ecological, economic and social dimensions.

Decision making for sustainable development calls for scientific support in the form of (i) anticipating the possible consequences of management options and (ii) identifying improved management solutions. Ex-ante impact assessment combines future driving force scenarios with alternative management scenarios, quantifies environmental, social and economic impacts using indicators, and conducts an integrated valuation and trade-off analysis of simulated impacts against pre-defined development targets [Helming et al., 2011a]. At the EU level, there has been a consistent movement toward the utilisation of Sustainability Impact Assessments (SIA). First the European Union Strategy for Sustainable Development [European Commission, 2001] voiced the need to look at how EU policies contribute to sustainable development and a year later the European Commission committed to perform impact assessments of all proposed major policies [European Commission, 2002]. SIA studies how factors such as policy, management or technology development affect the sustainability of a sector or value chain and helps to inform decision-makers about consequences of decision alternatives. The SIA methods with their balanced representation of social, economic and environmental sustainability are complementing existing environmental assessment approaches such as Life Cycle Assessment (LCA) [Guinée, 2002], carbon footprint [Wiedmann and Minx, 2008] or Paper Scorecards [WWF, 2007].

LCA is a tool to assess the environmental effects of products or services throughout their entire life – the so called cradle-to-grave perspective. LCA is used to compare product or service alternatives in order to identify the one causing the least environmental burden. The comprehensive inspection conducted through LCA is done to avoid shifting the problem of impacts [Finnveden et al., 2009] from e.g. the production to waste management or from Europe to India. LCA methods have experienced strong development since the early 1990's [Finnveden et al., 2009]. Work is being done to pool together expansions of LCA to cover the three dimensions of sustainability under Life Cycle Sustainability Assessment (LCSA) [Valdivia et al., 2011]. Besides the traditional LCA to assess the environmental impacts, life cycle costing (LCC) is proposed for assessing the cost implications of a life cycle and social life cycle assessment (S-LCA) for the assessment of social consequences. These developments broaden the capacity of LCA for SIA, but their main focus remains on product or specific production line assessments.

An important method for assessing resource-use efficiency is Material Flow Analysis (MFA), which aims to quantify the material flows and stocks of a selected substance in the anthroposphere (domain of human influence), for example chemical elements [OECD, 2008]. Processes are used in MFA as places where the flows merge and divide, also the places where stocks can accumulate. The system for study is delimited by a system boundary. MFA has been adopted for analysing flows on a national/regional scale or at a company level. Applied to the life cycle of a product it can represent the Life Cycle Inventory (LCI) as part of LCA. Both LCA and MFA traditionally share a restriction in being inventory based, not containing components of more advanced (dynamic) modeling. For example, the material flows of national MFA accounts are not modelled, but based on observed statistics. Mass balances can be carefully observed in MFA, but the indicators are constrained to a material flow basis [OECD, 2008] and MFA does not characterise processes in terms of sustainability besides resource-use efficiency.

The SENSOR (Tools for Environmental, Social and Economic Effects of Multifunctional Land Use in European Regions) project developed a Sustainability Impact Assessment Tool (SIAT) that causally links policy changes to land-use changes and the subsequent impacts on sustainability [Helming et al., 2011a; Helming et al., 2011b; Verweij et al., 2010]. SIAT implicitly includes impacts of forest resource management and uses a high level of aggregation in determining the impacts on production chains downstream of a forest. Of the work conducted so far, SIAT is methodologically the closest to the work presented in this paper.

While SIAT measures impacts using indicators, it doesn't include the process-based value chain perspective allowing for material flow calculation.

The goal of the sixth EU Framework Programme project EFORWOOD (2005-2010) was to develop a tool that implements sustainability impact assessment by combining quantified indicators of sustainability with value chain thinking. The aim was to use this tool to assess the sustainability impacts of policies, technological development scenarios or other such changes for the forest-based sector as a whole, or for value chains there in. None of the existing methodologies provide for a value chain based assessment of all three pillars of sustainability. This goal to achieve a more holistic assessment by connecting multiple sectors of activity and spanning different dimensions of sustainability lead to the development of the concept implemented by the Tool for Sustainability Impact Assessment (ToSIA). The general concept developed for ToSIA and a review of the methodological background is given in Päivinen et al [2012] and the functionality of these principles in ToSIA have been covered in more detail in Lindner et al [2010]. This paper documents the methodology and implementation of ToSIA from a software engineering perspective on modelling, including use of the Open Modeling Interface (OpenMI).

2 ToSIA IMPLEMENTATION

ToSIA assesses sustainability impacts of changes in Forest Wood Chains (FWC) using a combination of material flow calculation and indicators of environmental, social, and economic sustainability. ToSIA implements SIA by analyzing FWCs as chains of production processes which are connected by material flows of products. ToSIA serves as a transparent platform for assessing impacts of decision alternatives in policies or FWC technology and it can be applied at scales ranging from local to (inter-) continental. Target users of the tool and its assessments include scientists, consultants and policy makers. ToSIA includes a separate database and a database interface for value chain design and data entry, and also tools for performing cost-benefit analysis (CBA) and multi-criteria analysis (MCA) for interpreting the results produced in ToSIA.

In the core of the ToSIA tool is the dynamic calculation of material flows through a FWC, based on an initialisation of the chain. The flows bring out quantitative differences between processes or the impact of a varying flow for a single process when comparing between FWC alternatives. ToSIA multiplies the calculated material flows with quantified relative environmental, economic, and social indicator values for each of the processes along the FWC. The results are compared to results of runs performed with alternative assumptions. The comparison illustrates changes in sustainability indicator values. A change in an indicator result value in response to a changed external driver is a quantified impact.

ToSIA is implemented in the Java programming language, and it takes advantage of the Java version of the OpenMI standard version 1.4, which was the latest version available at the time when ToSIA was implemented. The Java language was chosen for the implementation because programs written in Java can be run on a wide variety of operating systems and hardware. This independency from hardware/software configurations is enabled by the Java Virtual Machine (JVM), which is tailored to each hardware configuration, but offers a standard interface toward Java programs. The CBA is implemented inside the ToSIA tool in Java but MCA is implemented in a separate tool programmed in C++ and it is linked to ToSIA via data files.

2.1 Open Modeling Interface (OpenMI)

The OpenMI standard is a software component interface definition that provides a standardized interface for the interlinkage of (computational) models [The OpenMI

Association, 2010a]. OpenMI was originally created in work that dealt with models related to hydrological flows of water. OpenMI has however been proven to be applicable in a wider environmental domain [Verweij et al., 2007]. OpenMI provides a means to define how much *value* of *what* is exchanged, *where* and *when* between models.

OpenMI utilizes a pull-based system for asking results from a linked model on a need basis. A model encapsulated as an OpenMI entity is called a *linkable component*, which gets input through *input exchange items* and provides results through *output exchange items*. These *exchange items* can be connected with *links*. A collection of linked *linkable components* is called a *composition* [The OpenMI Association, 2010b]. OpenMI provides the way to connect models, it requires a linked model to provide an answer to a request for output, but otherwise allows for freedom of implementation for the actual models encapsulated in *linkable components*. The way that exchange of results is implemented between models in OpenMI is demonstrated in figure 1. The pull to the values of component *C* triggers it to request the values of *B* (see *1*) to enable *C*'s calculation. *B* depends on *A* consequently requesting values from *A* (see *2*). Values are read from a database (*3*), returned to *B* (*4*) allowing *B* to perform its calculation (*5*), then results from *B* are passed on to *C* (*6*) to produce (*7*) the values originally requested.

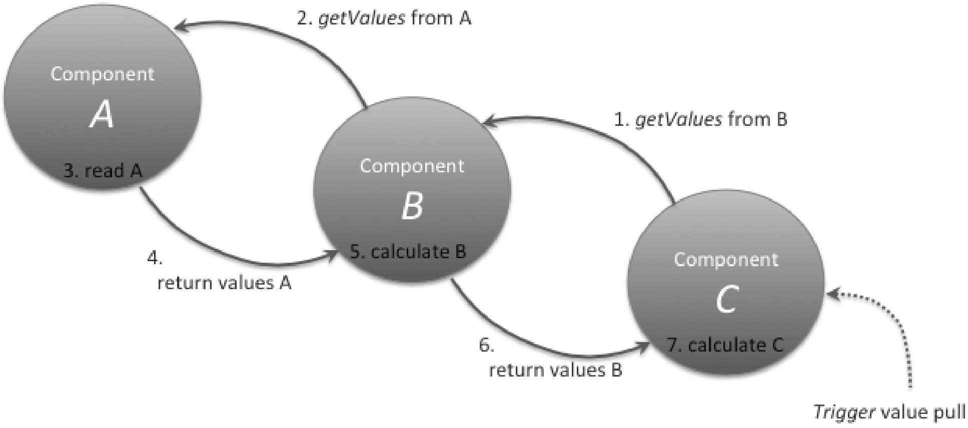

Figure 1. Chain of linked (model) components *A*, *B* and *C*.

The calculation of material flows is a result of “pulling” the trigger from a process that is the last in a value chain. This perpetuates the request “up” to the preceding processes in the chain until an answer is available. The “first” processes in the chain, i.e. those not linked “upwards”, should be able to give an answer independent of run time input. A received answer is then passed to the requestor, which after its own internal calculation then passes “down” its own answer. To calculate flows for all processes, we must “pull” on all processes that are not linked through a dependency path to ensure comprehensive calculation, as there can be many branches in the value chain.

2.2 ToSIA Approach for Calculating Cyclic Material Flows (Loops)

ToSIA is able to calculate material flow balances not only of tree-like value chains but also ones containing loop structures, as long as a non-infinity solution exists. Calculation is achieved by iterating through the loop(s) a limited number of times. Essentially this approximates the solution by calculating e.g. the first 200 iterations of a mathematical sum series that approaches a certain value (limit). The precondition for the mathematical series to be diminishing and not expanding is in the topology of a loop, e.g. a loop must have at least one “sink” – a vertex with an edge which is leaving the loop. A loop is shown in figure 2 between the two processes “Pleasure boating” and “Annual maintenance of sailing boat”, where a part of the used boats (output) of “Pleasure boating” goes as input to maintenance, and the maintained boats go back as input to the pleasure boating. Experimentally, we can test whether a series is converging or diverging by taking the values of three consecutive iterations and seeing if the sum of the first two is smaller or larger than that of the second and third. If the sum of the first two is smaller or equal than the last two, the series diverges (series sums to infinity); if larger, the series converges on a limit.

The OpenMI standard does not provide explicit support for a model to “follow” the situation of calculation in a composition. According to the component based approach, a component is not aware of its context. The loop calculation approach selected for ToSIA requires information on how many times *getValues* has been called on a *linkable component*, in order to be able to determine if it is located inside a loop. In ToSIA it was implemented as a counter that observes the number of times it has been asked for a result. Together with a maximum amount of iterations (corresponding to a desired accuracy) this can be used to break the otherwise perpetual recursive calls inside the loop and begin returning results.

In the current implementation of ToSIA, the user is allowed to define the chain topology without restrictions. As the amount of iterations that the loop can perform is restricted, we do not have a problem with eternal loops. However, the user can define a loop structure that performs an expanding series. The calculation result will only be an enormous flow, most likely so much so that a savvy user can understand the problem. The prototypes of ToSIA implemented loops in such a fashion, that they were iterated until the calculation result stabilizes to a value within the accuracy of the double type of java, or to an accuracy of one thousandth using an application of the test given before. However, the behaviour of this approach could create loops forming expanding series continuing until the system memory is exhausted (memory for call stack typically runs out first) and cause the application to crash. Therefore the approach using limited iterations described in the beginning of this chapter (2.2) was adopted.

2.3 Indicator Calculation

The collection of data for an indicator dataset to be used by ToSIA typically takes up the largest share of work time in implementing a complete assessment. While the indicator calculation is the key feature of ToSIA, from a calculation complexity point of view it is rather trivial. Essentially, the quantified indicator values relative to a unit of material entering a process are multiplied with the calculated material flows for each process. These per process indicator results can then be aggregated and grouped based on various process attributes such as country or phase of the value chain.

2.4 Example of a Value Chain Modelled with ToSIA

In figure 2 we have sketched a simplified value chain for the construction of wooden sailing boats, as a purely hypothetical example using improvised data and questionable system boundaries. We typically quantify an activity over one calendar year, and so in this example the calculated flows are raw materials consumed in the manufacturing of boats during one year. In the maintenance of boats the volume is that of all boats still in use; this is achieved using the loop. The assumption here is that a share of all boats in use is retired every year by burning them, and the rest go to annual maintenance. The loop here captures the volume of boats in use (and maintained) assuming a given removal ratio. Using the hypothetical data, we generated a situation where the amount of boats used was about 25-times the amount constructed annually (4% of total stock goes annually to incineration). Because of this difference in volumes, and using some sample indicators it is easy to envision a situation where the maintenance is actually a significantly higher source of employment than the actual construction.

When the example chain in figure 2 is constructed using OpenMI, the cases where there are many-to-one or one-to-many product connections (see output product of process “Pleasure boating”) need to be broken down. The output product is fractioned to as many *exchange items* as there are links. This is due to the fact that OpenMI only supports one-to-one connections between models' *exchange items*.

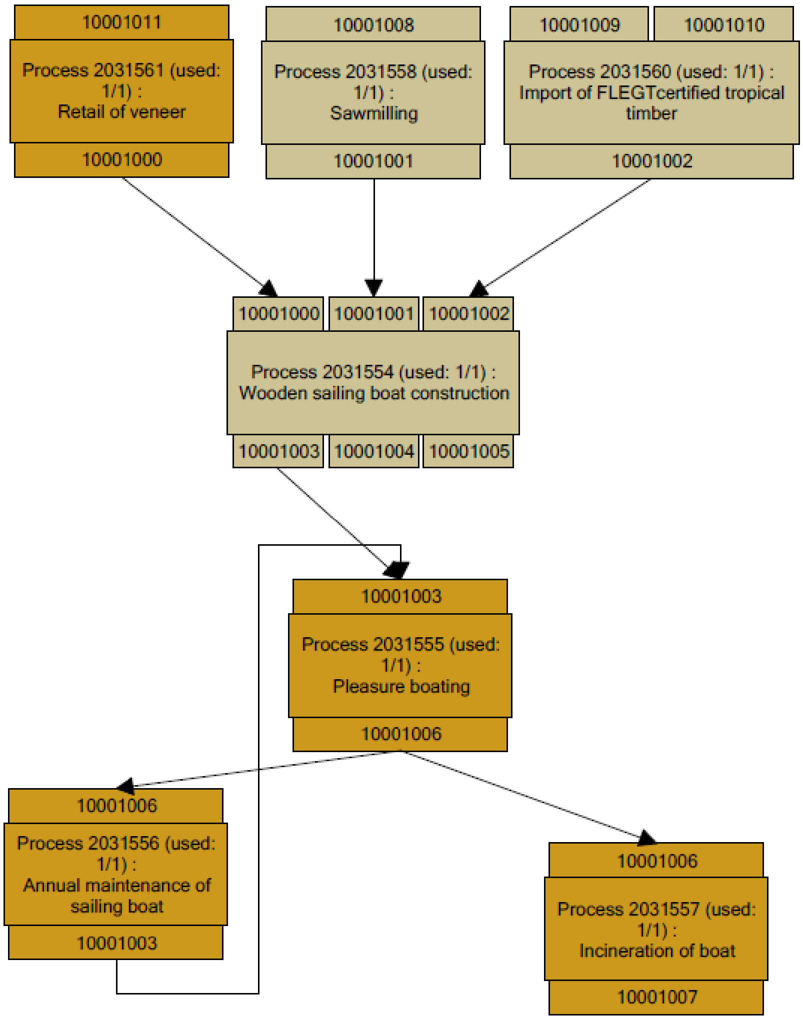

Figure 2. A simplified example chain for "Wooden sailing boat construction" is shown (screenshot from the ToSIA database client). The numbers above and below the processes correspond to products, some of which are linked to other processes, others are unlinked.

3 DISCUSSION ON ALGORITHMIC CHALLENGES

The first two prototypes of the ToSIA software released inside the EFORWOOD project used only standard Java. The prototyping approach was used because the first method development task was to show that the software tool concept that was being envisioned was valid and implementable. This need also influenced the choice of starting the tool design from calculation methodology development; a graphical user interface (GUI) was developed only for the final version. OpenMI was adopted for the final ToSIA version (of the EFORWOOD project). A key reason for choosing OpenMI was the idea that by its utilization it would be possible to more easily interface with other models, especially with future expandability in mind. Working with a more standardized approach was also considered an asset for maintainability.

OpenMI's original application was for water, a homogeneous and traceable element. In our value chains the material flows can be a variety of different products such as land (ha), felled timber (m^3), pulp (tons), furniture (tons) or even heat or electricity (MWh). While OpenMI does provide the way to express *what* is flowing, in order to retain a careful material balance when the flow of material is very heterogeneous we also defined a *base unit* (akin to water) in which all flows are calculated. When dealing with Forest Wood Chains our choice has been organic carbon, which is bound to living material through photosynthesis. We aim to maintain a material balance with regard to carbon, for every process – the amount of carbon coming into a process should logically be the same as the amount going out. An exception is photosynthesis itself, when trees grow, we do not report carbon from the atmosphere as an input product. This said, we do not keep the material flow balance with regard to other materials than the chosen *base unit*. A process where wood chips are dried results in a lighter product due to evaporation of water, and as we retain only the mass balance of carbon, this is acceptable. The changes in the properties of products are captured using product specific *conversion factors* and these are used during flow calculation to convert the products to e.g. carbon mass, real mass, volume, monetary value, etc. Each *process* in the value chain uses a specified unit for performing the indicator calculation, and thus all incoming products to a process need to be converted to this unit using the product specific conversion factors. By using the above described procedure ToSIA has tackled maintaining material flow balances and dealing with an assortment of different products.

The initialisation of the flow calculation is generally performed on processes with one unlinked input product, as the amount of input product clearly corresponds with the initialisation (whatever the unit). However, problems can be caused by situations where there are both unlinked and linked inputs; this is a complex issue for flow calculation. Users have raised the need to have the initialisation based on demand (relative to the linked input); this means that the initialisation would be a share relative to the sum of linked inputs from the chain. In value chains without loops, the initialisation does not pose a problem with either the static or dynamic initialisation. However, if loops are at play, the relative initialisation becomes a problem, because the amount of initialisation impacts the amount in the loop: is the share relative to the sum of input at the first iteration or the last one? If the first one, the share will not match the calculated flows in the end. If the last one, the input from the unlinked product increases with each iteration, thus introducing a new risk factor for making the loop perform an expanding series. If initialisation would be done as a relative amount of contribution to the loop on the first iteration, the above explained problem would not be a problem for calculation, but the explained share inconsistency would still exist. As an elegant solution for relative initialisation has not so far been found, we so far only allow absolute initialisations for value chains.

4 CONCLUSIONS

The first ToSIA prototypes proved that the material flow calculation through value chains using a wide variety of different units is a feasible and implementable concept. The final version of ToSIA demonstrated that this challenge could be successfully addressed using OpenMI. The main challenge in the adoption of OpenMI was how to deal with cyclical value chain topologies and prevent the software from entering eternal recursion as the OpenMI standard does not provide an out-of-the-box solution to handle deadlock. A solution to address this problem was presented in this paper. The slight increase in the complexity of the implemented software due to adoption of a standardized interface is seen to be offset by the gains of modularity that allows for easier expandability of ToSIA in the future. The current solution has proven to be very scalable and able to handle even large compositions – the largest one so far has been an EU wide FWC [Lindner et al., 2012] with nearly 2200 *Linkable Components* and far more *links*. ToSIA has been consciously developed in such a way as to lock down as few data related details as possible. Restrictions imposed only in requiring certain items of data to be present, but no demands are made to the content of that data. This creates a strongly data-driven approach, which allows application to different domains and at the same time removes the need for software development efforts when applying the tool for new case studies or environments. The less things are “tied down” by design, the more robust and reusable a tool will be.

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