

Dissertationes Forestales 322

Modelling for Sustainability Impact Assessment

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Academic dissertation

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ABSTRACT

Decision making for sustainable development calls for scientific support in anticipating the possible consequences of decision alternatives and identifying the trade-offs between these alternatives. At the EU level, there has been a consistent movement toward the utilization of Sustainability Impact Assessments (SIA). First, the EU Strategy for Sustainable Development voiced the need to look at how EU policies contribute to sustainable development. Next, the European Commission committed to perform impact assessments of all proposed major initiatives. SIA can be used to study 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 Tool for Sustainability Impact Assessment (ToSIA) was developed to achieve a holistic assessment method for structuring sustainability questions as value chains of interlinked processes that enable evaluating the impacts of changes in these chains. To evaluate these changes, indicators of ecological, economic and social sustainability are utilised to describe different sustainability dimensions. Selecting the preferred alternative within these calculated differences in sustainability indicators may imply trade-offs and is enabled for example by the multi criteria analysis appended on top of ToSIA. The use of ToSIA is demonstrated through its application in numerous case studies conducted by various organizations and scholars.

This thesis presents the developed ToSIA from a methodological point of view, describing how the method is used. ToSIA is the first software implementation of a method that combines material flow based value chain analysis with indicators of different sustainability dimensions and harmonized system boundaries. ToSIA is a valid tool for evaluating consequences of the difficult decisions ahead that need to be made as we strive to enact a transition both to a 1.5 degree warming future, as well as a more sustainable humankind.

PREFACE

Engineers are often blamed for developing technology first, and then trying to find good uses for it. The point of course is that a good engineer first identifies a concrete need, and only then develops a solution to address that need. Another consideration to bear in mind is the tendency to try to offer technological fixes for societal or systemic problems, because changing human behaviour is seen as too daunting a task. This thesis is thematically allotted to Forest Sciences, but it is quite inter-disciplinary. The background of the author is in computer science, where the focus is precisely on carefully constructed solutions. So, there are two parallel narratives to be found in this thesis: (1) the general method development track; and (2) the software development track. When the author started working, the thematic topic was given externally, along with some thoughts on how the solution should appear externally. This is also why this thesis does not start with a paper reviewing the state of the art in impact assessment. Such scoping exercises had already been carried out in the proposal development phase of the project, where the author of this thesis was eventually recruited to carry out this work. Where the author's creativity had freedom, was in how to solve the identified problem. This is very much reflected in the composition of this thesis as the articles included here reflect how the problem was solved and pick out those implementation details that were the most interesting from a design viewpoint.

This thesis focuses on the method and tool development aspects of the Tool for Sustainability Impact Assessment (ToSIA), as this has been the main focus of the author's contribution in the development of ToSIA. It does not focus on data or examples, the concrete problems that the method should solve. As an expert on the ToSIA methodology, the author has supported work on numerous case studies and has also occasionally been a co-author in papers where these case studies have been published. These co-authorship case-study papers have been excluded from this thesis, to keep the focus more clearly on the method development aspect. During the initial development phase of ToSIA there was constant interaction with parties responsible for field specific data. However, observation data from empirical case study work was not a basis model development, as ToSIA is not a model that tries to capture a specific natural phenomenon. Interaction focussed on the feasibility and meaningfulness of data collection, for what the method required – and this was a constant subject of discussion.

While in the end, a new method for sustainability impact assessment may be yet another technological fix that is not answering the core need for radical transformations in human behaviour and thinking, when faced with ongoing global challenges such as global warming and the sixth mass extinction.

ACKNOWLEDGEMENTS

The work described in this thesis has taken place in the context of the EC FP6 project EFORWOOD (2005–2010), EC NPP Project “Northern ToSIA” (2008–2011) and EC FP7 project CASTLE (2012–2016). A four-month grant (October 2018 & February–April 2019) for finalization of the thesis has been provided by the University of Eastern Finland (UEF) Faculty of Science and Forestry. The author arrived in the EFORWOOD project in January 2006 soon after the project had started (October 2005), and the scope of the project was set and the key objectives described. The author was the lead developer of the Tool for Sustainability Impact Assessment (ToSIA), where he was responsible for the software development. The prototypes of the software implemented by the author functioned as a proof-of-concept, but also were a significant factor in the conceptual design of the analysis method. The conceptual methodology design was a team effort, and while the author played a vital role, the effort was led by Marcus Lindner (work package leader in EFORWOOD) and his role in coordinating the design was significant and irreplaceable. As my direct supervisor, his ability to give difficult direct and critical feedback has been instrumental in my evolution from a software developer to someone writing the acknowledgements for this PhD thesis. The mutually respectful open-door policy of former European Forest Institute (EFI) director Risto Päivinen instilled in me a spirit of trust and collegial equality – “the EFI family spirit”- that I treasure to this day. Thank you for always having an open door and an open mind to discuss ToSIA and everything else. The eventual implementation of the ToSIA was a team effort to which many contributed: Sergey Zudin, Peter Verweij, Simo Varis, Wim de Winter, Pandu David, Mikko Savolainen, Teemu Turunen, Sanni Bomberg, Arttu Viljakainen, Jan-Erik Labbas, Joonas Kitunen, and Janne Kiljunen. The contribution of Diana Tuomasjukka (née Vötter), first through her PhD work, and later through her chairing of the ToSIA Management and User Group (TMUG) and the numerous ToSIA trainings that she has carried out, have been decisive for raising and maintaining people’s interest and capability to use ToSIA. The many people who have carried out case studies in the early stages of ToSIA have been instrumental in providing suggestions for improvements based on their hands-on experience – thank you (among others): Clemens, Wendelin, Michael, and Matias. Janni, thank you for having the courage to take on my ideas and brainstorm through our first joint paper. Thank you also to my numerous co-authors and EFORWOOD-survivors – without you this thesis would not have come to be. I would also like to thank Jörg Schweinle and Johannes Welling for instilling faith in me using a gigantic Excel spreadsheet demonstrating the ToSIA concept in my first month on the job that the concept could really work. A very warm thank you to my EFI family, who gave me a community in which to thrive and grow into something reminiscent of a researcher.

I also want to extend my thanks to CSC- IT Center for Research for giving me time off from my paid duties to work on finalizing this thesis. Completion of this work would not have been possible without this flexibility. I am grateful for the support of the UEF Faculty of Science and Forestry for the four-month PhD grant allowing a dedicated period for the finalization of the thesis – specific thanks go to the people who made the grant decision quickly allowing me to take advantage of this suddenly arisen opportunity. Thanks also to Tim Green for the English language check and helping me improve the readability of the text. Thank you to Timo Tokola for encouraging me to take this project on and to Gert-Jan Nabuurs for pushing me in this direction in the first place.

Looking back, being project manager of the Marie Curie Initial Training network CASTLE (Careers in Sustainability Excellence) and seeing the progress of the 15 early-stage researchers working on their PhDs probably was a key impetus for me to join suit. I am so happy to have had the chance to have worked with you all. Thank you Alexandra, Anna, Anna Liza, Dunsin, Francesca, Frank, Gediminas, Genevieve, Heather, Jens, Pau, Philipp, Salvatore, Teresa, and Qianyu Li (Amber)!

My father's parents did not go to high school, but all three of their children got Master's degrees. My father was the first in our family to get a PhD, and now both of his children will also (hopefully) get PhDs. Thank you Dad for having the patience to answer my never-ending questions in my youth, especially when it was time to go to sleep! I grew up in an environment where curiosity was nurtured, and education was appreciated. I walked my own path to get here, but I've always known my family has my back. Thank you Mom, Dad and Jonna. There is one person who would be very proud of me today, but who is not here to see this day, and that is my Mom. "Live as die tomorrow. Learn as live forever" – I am trying Mom! I love you and miss you.

My beautiful little daughters Selma and Aina – you are the light of my life! You motivated me to finish this thesis, so I can again spend more time with you – the best possible reason in the world. Every day, you make me proud and happy to be your father – my favourite job in the whole world.

Dear Saba, I stood by you when you took this path before me. Watching you complete this exercise has shown me that I can do this too. Thank you for supporting me, being with the kids while I sit inside fixed to the computer screen. Thank you for giving me a push when I needed one. I love you. I hope we will now have many years of smooth sailing ahead, living life to its fullest!

The mathematical formulas in this thesis have been mostly written by Sergey Zudin, for paper III of this thesis and the Appendix to the summary. Figure 2 was made by Wendelin von Gravenreuth (né Werhahn-Mees) for an unpublished document in 2010.

Turku, April 2021

Tommi Suominen

LIST OF ORIGINAL ARTICLES

- I. **The first paper** (2010) published the developed ToSIA methodology.
Lindner, M., Suominen, T., Palosuo, T., Garcia-Gonzales, J., Verweij, P., Zudin, S., Päivinen, R., (2010). ToSIA – A tool for sustainability impact assessment of forest-wood-chains. Ecological Modelling, 221: 2197–2205. <https://doi.org/10.1016/j.ecolmodel.2009.08.006>
- II. **The second paper** (2017) examined a case study where ToSIA was used to analyse the sustainability trade-offs of introducing cascade use of wood to a situation where it had previously been used for energy.
Suominen, T., Kunttu, J., Jasinevičius, G., Tuomasjukka, D., Lindner, M., (2017). Trade-offs in sustainability impacts of introducing cascade use of wood. Scandinavian Journal of Forest Research, 32(7): 588–597. <https://doi.org/10.1080/02827581.2017.1342859>
- III. **The third paper** (2021, submitted manuscript) explains from the methodological side, how ToSIA addresses the issue of calculating cyclical material flow using OpenMI, relevant in, for example, calculation of value chains dealing with recycling or cascade use.
Suominen, T., Zudin, S., Lindner, M., Verweij, P. (2021). Modelling circular value chains - using OpenMI for calculation of cyclic model linkages in the Tool for Sustainability Impact Assessment (ToSIA). Submitted manuscript.
- IV. **The fourth paper** (2010) published a way by which the topology of the value chain can be used for calculating the share of impacts each process along the value chain contributes to a selected product’s “sustainability backpack” – a process also known as allocation.
Palosuo, T., Suominen, T., Garcia-Gonzales, J., Lindner, M., (2010). Assigning results of the Tool for Sustainability Impact Assessment (ToSIA) to products of a forest-wood-chain. Ecological Modelling, 221: 2215–2225. <https://doi.org/10.1016/j.ecolmodel.2010.03.020>

The author’s role in the original articles

Paper I: Mr. Suominen was the person responsible for designing and implementing ToSIA, which is presented in this paper. This paper embodies nearly four years of work on the tool development by Mr. Suominen. While Mr. Suominen commented on and checked the text, the first author was primarily responsible for writing the text. **CRedit:** *Conceptualization; Data curation; Methodology; Software; Validation; Writing – review & editing.*

Paper II: Mr. Suominen conceptualized the study and the paper and presented the initial idea at a conference in 2015. The second author was responsible for data collection, and practical implementation of the presented case study. Mr. Suominen had the overall responsibility for the paper and wrote a significant part of the paper. It should be noted that the writing was still a team effort. The third author was primarily responsible for aspects

related to carbon accounting. **CRedit**: *Conceptualization; Funding acquisition; Methodology; Project administration; Resources; Software; Supervision; Validation; Writing – original draft; Writing – review & editing.*

Paper III: Mr. Suominen conceptualized the paper, has been responsible for the presented method development and wrote the majority of the paper. The co-authors have participated in the method development that is presented here, and have written targeted paragraphs according to their expertise or provided input on improving the overall quality of the manuscript. Sergey Zudin prepared the mathematical equations. **CRedit**: *Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Validation; Writing – original draft; Writing – review & editing.*

Paper IV: Mr. Suominen was responsible for designing and implementing ToSIA, to which this paper adds a methodological feature. Mr. Suominen was also responsible for conceptualizing the allocation approach presented in this paper together with the first author. Mr. Suominen actively commented on the manuscript and its figures, but writing was mainly the responsibility of the first author. **CRedit**: *Conceptualization; Data curation; Methodology; Software; Validation; Writing – review & editing.*

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ABBREVIATIONS

CBA	Cost–Benefit Analysis
CRedit	Contributor Roles Taxonomy
DBC	Database Client
DSS	Decision Support System
EFI	European Forest Institute
EFISCEN	European Forest Information Scenario Model
EPD	Environmental Product Declaration
ESC	European Sustainability Criteria (prior to 2016); Emission Saving Criteria (>2016)
EU	European Union
FWC	Forest Wood Chain
GHG	Greenhouse Gas
GIS	Geographic Information System
GUI	Graphical User Interface
GVA	Gross Value Added
IPCC	Intergovernmental Panel on Climate Change
JSON	JavaScript Object Notation
JVM	Java Virtual Machine
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
MCA	Multi-Criteria Analysis
MFA	Material Flow Analysis
MIPS	Material Input per Service-unit
NPV	Net Present Value
ORM	Object Relational Mapping
PA	Policy Analysis
SDG	Sustainable Development Goal
SETAC	Society of Environmental Toxicology and Chemistry
SFM	Sustainable Forest Management
SIA	Sustainability Impact Assessment
ToSIA	Tool for Sustainability Impact Assessment
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environment Programme
XML	eXtensible Markup Language

INTRODUCTION

General background

We, the people of the planet earth, are using the natural resources of this planet unsustainably (Meadows et al. 1972). We globally use 1.75 times (Global Footprint Network 2020), 2.8 times in the European Union (EU) (Vandermaesen et al. 2019), more natural resources than the planet is able to regenerate, which if not halted, will lead to resource depletion. Unsustainable behaviour was previously attributed to a lack of knowledge. That argument holds no more. The behaviour is nowadays being justified as a development phase in transitioning to a more sustainable society. Sustainable use of natural resources, climate change, circular economy, bioeconomy – work on these topics share the same root – a concern that we are devouring the resources of this planet beyond its regenerative capacity and in doing so hinder the planet's ability to support human life. Sustainability assessment (Klinglmair et al. 2014) and sustainability science (Jerneck et al. 2011) are seen as a way to address these challenges.

Climate change among other socio-economic crises is a result of our past and present unsustainable behaviour. The 2018 Intergovernmental Panel on Climate Change report (IPCC 2018) and the ensuing press coverage proclaimed loudly to the general audience what scientists have been saying for a long time – i.e. that we must make radical changes to stay within 1.5°C of climate warming. Natural resources such as forests can play a significant role in climate change mitigation (Grassi et al. 2017; Nabuurs et al. 2017).

To maintain a viable planet for all, resource consumption needs to be at a level where the regeneration of natural resources is higher or equal to their consumption – one of the first definitions of sustainability came from forestry in the form of the concept of sustainable yield, which was introduced over 300 years ago by Carl von Carlowitz (1713). Carlowitz's motivation for developing the concept of sustainable yield was to address concerns about economic sustainability. The mining sector in his region was going out of business due to a lack of wood for smelting the mined ore. This wood shortage had been caused by unsustainable harvesting combined with a lack of forest regeneration. Depletion of ecological resources had thus become an economic concern, and which in turn was in danger of becoming a social concern – when an economic activity decreases, people lose their jobs, and their capacity to meet their basic needs erodes. The three sustainability dimensions are intimately interlinked.

It was the Brundtland Report “Our Common Future” (WCED 1987), prepared before the 1992 United Nations Conference on Environment and Development (UNCED), that brought the three sustainability dimensions into public discussion. The report also introduced the perhaps most quoted definition of sustainable development: “*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).

Utilization of natural resources either takes the form of activities to meet primary needs such as food, water, shelter or then livelihoods and economic activity for various reasons. A dominant feature of economic activity is that it needs to cover its costs and typically generate a profit. An economic activity that makes a financial loss cannot be sustained without continuous input of capital, e.g. in the form of subsidies. Except for those activities needed to satisfy primary needs, in the current capitalist economy activities need to be economically sustainable in order for them to persist.

The majority of people care about the environment also because the environment has intrinsic value, independent of its impact on people and its socio-economic benefits. This majority of people would like to see us restructure our production systems and consumption patterns to be less destructive to the environment. On one hand, an environmentally improved production system will most likely not succeed if it is not economically sustainable – and therefore will not result in improvement of environmental sustainability – if no one uses the solution. On the other hand, an economically profitable activity might be prohibited if it is not seen as socially or environmentally sustainable. A lack of environmental sustainability may lead to a lack of economic sustainability, and in the current capitalist society, these two combined may result in social unsustainability. What we ultimately want to avoid, because our survival depends on it, is a degraded environment that is not healthy to live in and is not capable of producing the resources necessary to sustain the present levels of human and non-human life. The question of unequal distribution of wealth (Hickel 2020) can mean that the rich can secure their access to resources by for example institutional arrangements or by military force, resulting in unequal distribution of resources necessary to sustain human life. This is already taking place today, further exacerbating social inequality – something that is nearly synonymous with social unsustainability.

Despite the general acceptance of the definition of sustainable development provided by the Brundtland Commission (WCED 1987), sustainability is an elusive concept to concisely define. In discussing the nature of the sustainability concept, Vucetich and Nelson (2010) argue that we can never give a final definition of sustainability. Instead, they define two extremes of sustainability, called virtuous and vulgar sustainability. Virtuous sustainability is understood as exploiting “as little as necessary to maintain a meaningful life”, while vulgar sustainability as exploiting “as much as desired without infringing on the future ability to exploit as much as desired”. Vucetich and Nelson (2010) say that sustainability is a moving target that changes with time like the concept of justice, which is said to be “varied, indefinite and evolving”. These definitions perhaps focus more on planetary capacity for natural resources and ecological sustainability, but how do we apply these definitions to the social sustainability dimension? One wonders if Vucetich and Nelson thought to socially exploit “as little as necessary to maintain a meaningful life” or exploit “as much as desired without infringing the possibility for future ability to exploit” – probably not. Sala et al. (2015) compile various more balanced definitions of sustainability science, including the one from Sala et al. (2013): “*solution-oriented discipline that studies the complex relationship between nature and humankind, conciliating the scientific and social reference paradigms which are mutually influenced- and covering multi temporal and spatial scales. The discipline implies a holistic approach, able to capitalize and integrate sectorial knowledge as well as a variety of epistemic and normative stances and methodologies towards solutions’ definition*”.

Addressing the problem – methodologies to assess sustainability impacts

The concept of sustainable resource use proposed by Carlowitz (even if only yield-based) was a revolutionary idea in the 18th century. Nowadays, it would fit into the definition of “vulgar sustainability” (Vucetich and Nelson 2010) and address only one sustainability dimension. Following the Earth Summit in Rio de Janeiro, Brazil in 1992, the broader societal orientation on sustainable development was also introduced with the advent of principles for sustainable forest management (SFM). These principles take into account the three pillars of sustainability: economic, social and environmental (Hahn and Knoke 2010).

The United Nations has recognized the integrated nature of the three sustainability dimensions and have formulated the current sustainability challenges facing mankind into 17 problem-oriented sustainable development goals (SDGs) as part of the 2030 Agenda for Sustainable Development (United Nations 2015). Though these goals are defined in a very general way, their value lies in the international political commitment to work towards these goals. The SDG 15 is “*Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss*” (United Nations 2015). Baumgartner (2019) discusses the relevance of forest management to the other SDGs and shows that forest management can have a positive or negative impact on sustainable development and recommends use of integrated assessment approaches for ex-ante assessment of intended forest-related policies.

Greta Thunberg personifies the frustration shared by many people on how the actions taken to combat climate change are too slow and too little. Getting people out of their comfort zones, and changing their behaviour is notoriously difficult. However, it is one thing to get people to change their private actions on their own volition, but achieving systemic change is a challenge on another level of complexity (van Tulder and Keen 2018). Achieving radical change in a profit-focussed and economic growth-oriented world can be difficult. Companies may fall into the “incumbent’s curse” (Chandy and Tellis 2000): why should large dominant companies invest in changing things, when the profits are safer and better by maintaining the status quo? Companies may even reject change towards more sustainable solutions, even against the views of their own leadership – this inability to change has been termed the “Kodak-effect”, after “the experience of the leading photography company that created the world’s first digital camera but was not able (and/or willing) to change its business model accordingly” (van Tulder and Lucht 2019), consequently leading to its bankruptcy in 2012. Hengelaar (2017) highlights how small businesses often take the role of pushing more radical and transformative innovations forward, while the large incumbents prefer stability and incremental change.

Policies can result in unintended consequences, e.g. through trade-offs that were initially not thought of (Timko et al. 2018). This falls in line the EU call for ex-ante assessment of policies (see the following section: Sustainability impact assessment – a European perspective on the policy need for tools). The same can be said for ambitions of companies to innovate their practices for improved sustainability – there are plenty of pitfalls (Tura et al. 2019). As Mortimer (2016) argues, often “good intentions are not enough”. We need systems thinking – to understand what affects what in complex interlinked systems (Halog and Manik 2011; Little et al. 2019). For example, Nilsson et al. (2016) have developed a scheme for evaluating the interdependencies of the SDGs on each other, and many have worked on the mapping the concrete correlations between the UN SDGs (Lo Bue and Klasen 2013; Pradhan et al. 2017; Neumann et al. 2018). The difficulty of achieving systemic changes towards a more sustainable future have given rise to a dedicated field of research: sustainability transitions (Markard et al. 2012).

Ultimately, decision makers and politicians are responsible to the people who pay their salaries to make good, responsible decisions just like company CEOs and boards are responsible to the shareholders to ensure long-term financial sustainability of a business. Both public and corporate decision makers need to weigh environmental, economic, and social consequences of decisions, and herein lies the main motivation for the work presented in this thesis: the development of a method for informed science-based decision making – so that the change we create is made responsibly. The integrated nature of the sustainability challenges means that the solutions to address these challenges need to have a holistic

perspective that is able to support decision making by presenting alternatives with their sustainability trade-offs and impacts. This need is valid at all levels: from decisions made about designing individual products, to decisions concerning industrial sectors, to decisions taken at the national and international levels. The need is also valid for different types of decision makers: researchers, industries, and public servants.

Sustainability impact assessment – a European perspective on the policy need for tools

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 scenarios of future trends with alternative management options, quantifies environmental, social and economic impacts using indicators, and conducts an integrated valuation and trade-off analysis of simulated impacts against predefined development targets (Helming et al. 2011a). At the EU level, there has been a consistent movement toward the utilization of Sustainability Impact Assessments (SIA). First, the EU 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 can be used to study 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 can be used to complement existing environmental assessment approaches such as Life Cycle Assessment (LCA) (Guinée 2001; Finnveden et al. 2009; Guinée et al. 2011; McManus and Taylor 2015), Material Flow Analysis (MFA) (Hendriks et al. 2000; OECD 2008), and ecological, carbon, and water footprints (Wiedmann and Minx 2008; Galli et al. 2012).

The SENSOR (EU FP6) project developed a Sustainability Impact Assessment Tool (SIAT) that causally links policy changes to land-use changes and the subsequent impacts on sustainability (Verweij et al. 2010; Helming et al. 2011a, b). SIAT implicitly includes impacts of forest resource management and uses a high level of aggregation in determining the impacts on production chains downstream from a forest.

Uthes et al. (2010) compared the policy relevance of three integrated assessment tools for the assessment of impacts of land-use changes: SIAT, SEAMLESS-IF and MEA-Scope. The study concluded that the choice of tool depends on the policy question asked and none of the tools is suitable for answering all scientific questions nor all policy questions. The tools faced a trade-off concerning whether to analyse a single sector in detail (SEAMLESS-IF, MEA-Scope) or to attempt a more multidisciplinary but generalized approach (SIAT). While measuring impacts using indicators, none of these tools included a process-based value chain perspective allowing for material flow calculation, bridging all the different scales.

The goal of the EFORWOOD (EU FP6) project (2005–2010), was to develop a tool that implements sustainability impact assessment by combining quantified indicators of sustainability with value chain thinking covering entire value chains (Päivinen and Lindner 2006; Rosén et al. 2012; Päivinen et al. 2012). With this tool, EFORWOOD aimed at assessing the sustainability impacts of policies, technological development scenarios, or other such changes for the forest-based sector as a whole, or for value chains therein. The existing methodologies were not fully able to provide for a value chain based assessment of the three pillars of sustainability, while covering all different phases of the value chain from

forest management to the products' end of life. 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 new concept: the Tool for Sustainability Impact Assessment (ToSIA). ToSIA was made to support decision making by weighing and presenting decision alternatives with their impacts and trade-offs. The aim was to create a scalable method that works for individual products, sectors, or countries, and for researchers, companies, and policy makers. Development of ToSIA and collecting data on the European forest-wood sector was a large endeavour, with over 100 people from more than 40 organizations participating in this work.

In reviewing the policy relevance of European Impact Assessment (IA) tools a few years after Uthes et al. (2010), Podhora et al. (2013) still found that “the tools primarily addressed environmental impact areas, less economic and least social impact areas”. Additionally, “research on IA tools is scattered across separate scientific communities”. Finally, a thorough review and a way forward from fragmentation in the development of sustainability assessment, is delivered by pulling together the varied development trends and proposing “a systemic framework for sustainability assessment” (Sala et al. 2013, 2015).

Life Cycle Assessment (LCA) and Life Cycle Sustainability Assessment (LCSA)

The use of LCA is very widespread across topical domains, and it is the method that most researchers and the public have come into contact with. LCA is also widely used for forest products to assess the environmental effects of products or services throughout their entire life – the so-called cradle-to-grave perspective (Finnveden et al. 2009; Heinemann 2012; de la Fuente et al. 2017a). LCA can be used, for example, to compare product or service alternatives in order to identify the product/service causing the least environmental burden. De la Fuente et al. (2017b), for example, compare two alternative forest biomass supply chains. LCA can also be used to identify environmental sustainability hotspots within a production chain. LCA methods have experienced strong development since the early 1990s (Finnveden et al. 2009; McManus and Taylor 2015). Life Cycle Impact Assessment (LCIA), which is a phase in an LCA assessment, is used to operationalize LCA for business and policy making (EC-JRC-IES 2010a; Wardenaar et al. 2012). Work of the United Nations Environment Programme (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC) Life Cycle Initiative attempts to pool together expansions of LCA to cover the three dimensions of sustainability under Life Cycle Sustainability Assessment (LCSA) (Ciroth et al. 2011). Besides the traditional LCA to assess the environmental impacts, LCSA consists of life cycle costing (LCC) for assessing the economic implications of a life cycle and social life cycle assessment (S-LCA) for the assessment of social consequences. While the need for LCSA studies is continuously called for (Karvonen et al. 2017), Luu and Halog (2016) state that still “in most life cycle assessments conducted, the economic and social pillars have been less considered with due preference to environmental aspects”. The development of LCIA and LCSA broadens the capacity of LCA for SIA, and is catching (if not caught) up to the issues that ToSIA was designed to solve. Even though the idea when designing ToSIA, was to create a new stand-alone method, to improve on previous efforts, ToSIA can in fact be used as a way to carry out LCSA.

Material Flow Analysis (MFA)

An established 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, for example, for elements such as carbon (Hendriks et al. 2000; OECD 2008). Processes are used in MFA as places where the flows merge and divide, and also as places where stocks can accumulate. A studied system is delimited by a system boundary. MFA has been adopted to analyse flows at a national/regional scale and at a company level (Fischer-Kowalski et al. 2011; Kovanda et al. 2012). Applied to the life cycle of a product it can be used to support the Life Cycle Inventory (LCI) part of LCA. Mass balances can be carefully observed in MFA, but the MFA indicators are constrained to a material flow basis. However, in combination with LCA as, for example, in the study on increasing wood cascade by Bais-Moleman et al. (2018), more indicators can be covered, but still typically delimited to environmental aspects.

Aims of this work

The work presented in this thesis focusses on the method and software development aspects of the Tool for Sustainability Impact Assessment (ToSIA), as this has been the main focus of the authors contribution in the development of ToSIA. Deriving from this, *the over-arching research question of this thesis is: can a method be designed and implemented to address the identified gap in the state of the art of Sustainability Impact Assessment?* This question is broken down into four more detailed research questions below. These questions first focus on the core method development, and then examine two specific methodological aspects that have required more effort to resolve.

- RQ1: How can material flow analysis and three-dimensional sustainability indicators be combined with consistent system boundaries in order to assess sustainability impacts of changes in value chains? (Papers I, II)
- RQ2: How can the method be used to perform ex-ante sustainability assessment or highlight sustainability trade-offs between alternatives (in technology, policy, etc)? (Paper I, II)
- RQ3: How should value chains with several lifecycles, including cascade use and recycling/repurposing be calculated and handled? (Paper II, III)
- RQ4: How can one product from a larger integrated production system be singled out, and allocated a proportion of the calculated indicator results, with flexible allocation criteria? (Paper IV)

The focus of this thesis is on the software tool development and sustainability assessment methodologies. First, the method is introduced at a general level and contextualized. This is followed by a practical step-by-step explanation of applying the methodology and the concepts related to those steps. This is largely based on paper I. Second, more methodological detail is given indicators and the value chain concept is thoroughly described, including careful examination of cyclic value chains (based on paper III). Software development issues come in to play with regard to how the value chain process interlinkages are built using OpenMI, and this is followed up with a section summarising the large amount of software development work carried out over the timespan of ToSIA development. To contrast the

conceptual development, the next section provides a view on practical application from papers II, III, and IV. First the focus is on cascading value chains, then cyclic value chains, and finally the developed topological allocation algorithm. The ensuing discussion focusses on directly addressing concerns related to each of the four research questions. It could be argued that the coverage of the topic is not complete without exemplifying its range of applicability through case studies. So, after more conceptual concerns we turn to a brief overview of how ToSIA has been tested and validated through varied case studies. After some thought on methodological improvements and thought on a next generation of modelling solutions, I finish the summary with conclusions.

THE DESIGN OF ToSIA

The development of tools for analysis of sustainability impacts is collectively here called the Tool for Sustainability Impact Assessment (ToSIA). According to the classification provided by Sala et al. (2013) (Figure 1), ToSIA is a combination of tools, *methods*, *methodologies* and a *framework*; a documented way of carrying out sustainability impact assessment. Figure 2 illustrates this multifaceted nature and structure of ToSIA. While ToSIA initially referred

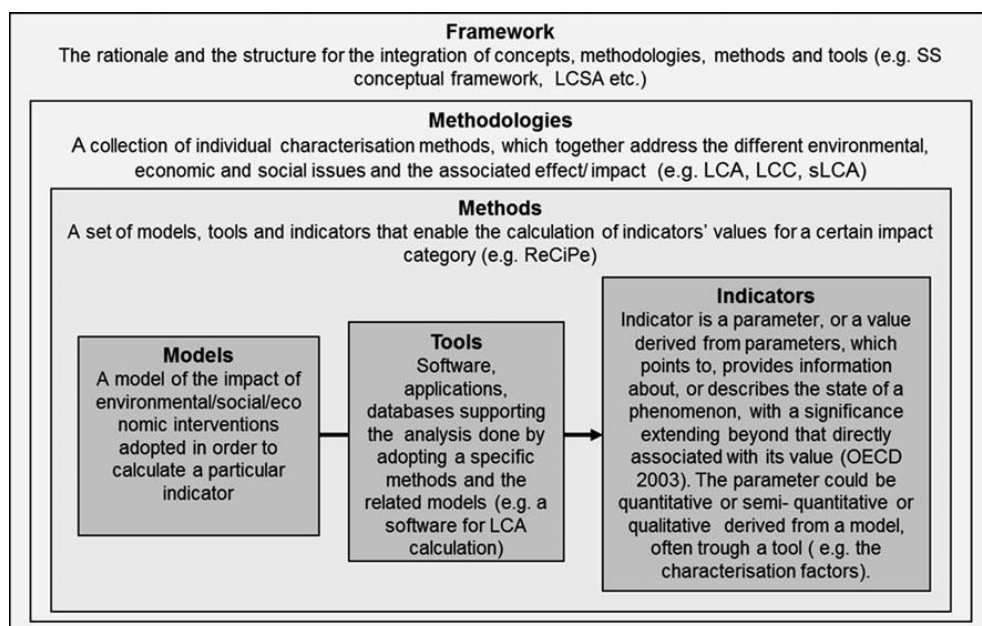


Figure 1. Definition of concepts for use in Sustainability Assessment (Sala et al. 2013), from an LCA perspective, where e.g. *Models* and *Tools* are seen to be indicator/impact category-specific. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature; The International Journal of Life Cycle Assessment. Sala S, Farioli F, Zamagni A Progress in sustainability science: lessons learnt from current methodologies for sustainability assessment: Part 1, © 2013.

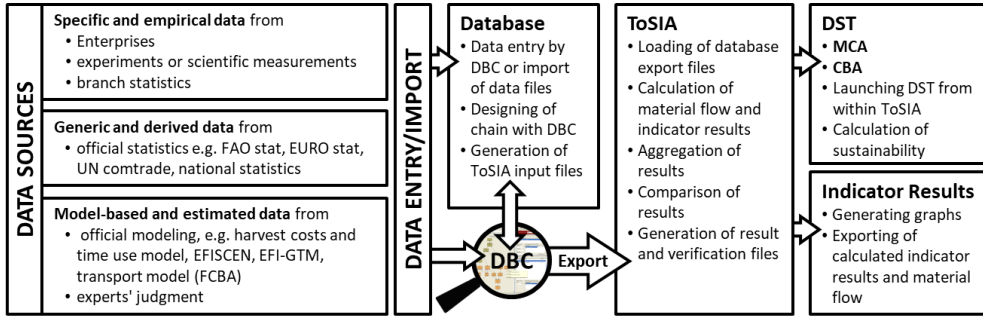


Figure 2. The ToSIA Toolbox version 1.0 (Unpublished, Werhahn-Mees 2010).

to the core calculation method, it was also expanded to cover everything created around it to facilitate its use. Initially the calculation tool was technically separate from the databases and the database client (DBC) used to enter and manipulate data. Data for calculation from the database was fed via XML files. The DBC and the calculation part of ToSIA were later integrated. More information on the evolution of the software can be found in the section on *ToSIA software development*. So in reference to Figure 1, from Figure 2 we can see that for ToSIA version 1.0 the calculation software was a **tool**, the broader analysis concept embodied by the tool was a **method**; the collection of integrated methods for further analysis (CBA, MCA) was a **methodology**. The whole approach comprised a **framework** for carrying out

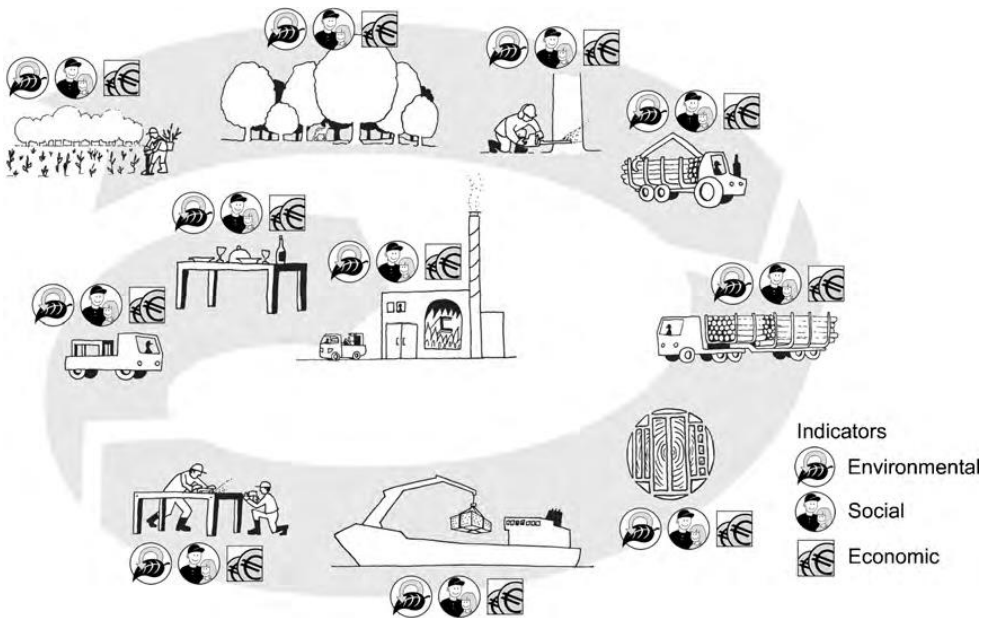


Figure 3. Graphical illustration of a forest wood chain with sustainability indicators describing each process (paper I, Figure 1). (Figure originally published by Lindner et al (2010). *Ecol Modell* 221: 2197–2205.)

Sustainability Impact Assessment (SIA) on a par with LCSA – but including further possibilities for analysis, e.g. the participatory MCA.

ToSIA is designed as a *framework* that can be applied to any (material) flow-based value chains, even if the approach was developed in the forest wood chain (FWC) (Figure 3) context and has been most extensively applied to them (Lindner et al. 2012; Päivinen et al. 2012). ToSIA serves as a platform for assessing impacts of decision alternatives in policies or value chain technology and it can be applied at scales ranging from local to (inter-)continental. The general ToSIA concept was first introduced at a conference in 2005 (Päivinen and Lindner 2006); a review of the methodological background was later given by Päivinen et al. (2012) and the concretization of the ToSIA method is covered in paper I of this thesis. Further technical detail on the ToSIA implementation is given by paper III of this thesis. The developed approach is flexible and generic. 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 the flow volume of each process with indicators of environmental, social, and economic sustainability (see Figure 3), 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 technologies or of redistributing resources between alternative/competing uses. By structural complexity, we can divide value chain topologies (paper I) into three categories:

- 1) Tree-like topologies, which go from resources through primary and secondary production, wholesale/retail to end users as products followed by their collection and end of life. Or the same in reverse, looking downstream from, for example, consumption, and tracing towards where the raw materials come from.
- 2) Cascading value chains, which consist of two or more interlinked value chains of category 1, where end of life is replaced by reuse or recycling as input to the next value chain (Sirkin and ten Houten 1994).
- 3) Cyclic value chains where the output of a value chain is an input to itself. Additionally, it can also be an input to end of life or a category 2 structure.

This categorization of structural complexity is introduced here for the purpose of structuring the work presented in this thesis. While this categorization applies to structural complexity, a value chain of 2200 processes of category 1 will probably be perceived as more complex by a user than a value chain of 20 processes of category 3. The categorization draws its ideas from the Cascade Chain concept introduced by Sirkin and ten Houten (1994), where “resource economy is achieved through the step-by-step utilization of resource quality at its highest possible level until the resource is fully exhausted”. Sirkin and ten Houten (1994) also introduce the “recirculation of resources” using the concept of salvageability, which “concerns the degree to which the resource qualities of a substance, material or product can be recirculated”. This means that “the otherwise two-dimensional cascade concept becomes cyclic”, and falls into the introduced category 3.

The dynamic calculation of material flows through a FWC is based on an initialization of the chain from its beginning or end (e.g. a given forest area, or amount of end-product). The flows bring out quantitative differences between alternative processes or the impact of a varying flow for a single process when comparing between FWC alternatives. ToSIA multiplies the calculated material flows with relative environmental, economic, and social indicator values (see the following chapter) for each of the processes along the FWC. The

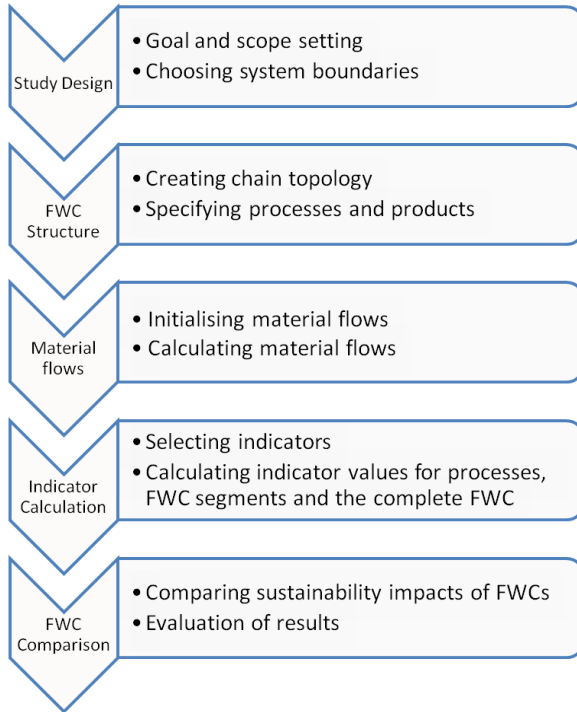


Figure 4. The workflow of carrying out a study with ToSIA (paper I, Figure 2). (Figure originally published by Lindner et al (2010). *Ecol Modell* 221: 2197–2205.)

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.

Next, the fundamentals on application of ToSIA (RQ1) are given, followed by a more detailed look at the developed methodology. This is followed by a description of the application of ToSIA on a cascading value chain, and the sustainability trade-offs such a case entails (RQ2). Next, more detail on calculating cyclical material flows is given with explanatory examples (RQ3). This is followed by a description of the topological allocation algorithm developed specifically for ToSIA (RQ4). Finally, an overview of the evolution of ToSIA software between 2006 and 2018 is described.

Assessing the sustainability impacts of changes in value chains, by combining material flow analysis and sustainability indicators with consistent system boundaries (RQ 1, paper I)

Paper I described the developed ToSIA methodology and its application in a nutshell. More practical details on how to use ToSIA (version 1.0) can be found in the EFI Technical Report 48 (Green et al. 2011). The workflow for how a study is carried out is described in Figure 4. The concept of a value chain and how we describe it in ToSIA is illustrated in Figure 5.

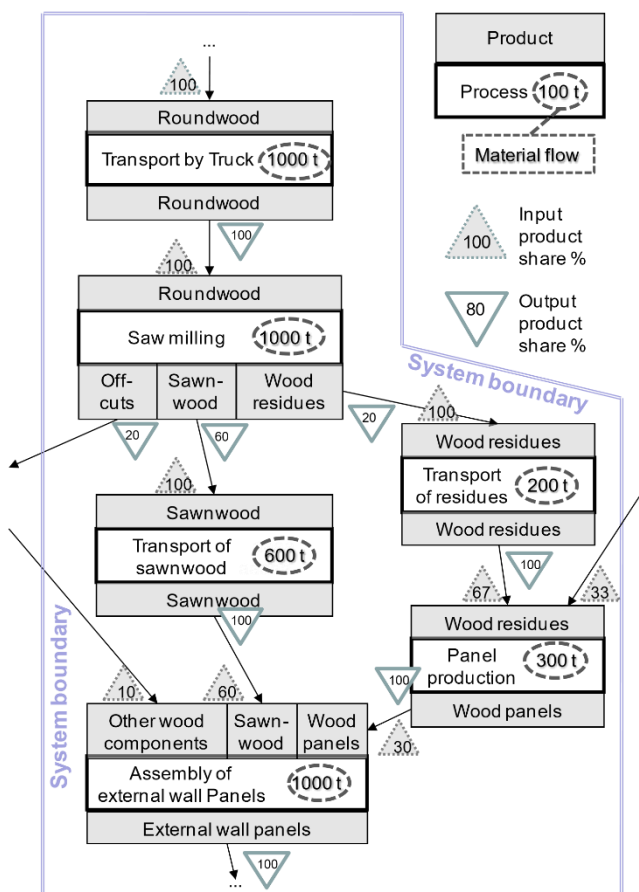


Figure 5. Extract of the FWC topology showing the selected processes and products and their connections. Product shares for input and output products enable the calculation of material flows along the FWC (paper I, Figure 3). (Figure originally published by Lindner et al (2010). *Ecol Modell* 221: 2197–2205.)

The following gives a description of a practical use of ToSIA, as per Figure 4.

1. Study design

a. Goal and scope of the study

- i) The chosen “what if” questions that a study wants to answer shape the alternatives to be defined and compared, and the selection of processes that are focussed on more intensively. Without alternatives, there are no changes, or consequent impacts to be evaluated. The alternatives can arise from technological innovations, resource management alternatives, or new policies, and they can be assessed retrospectively (ex-post) or prospectively (ex-ante). At its simplest, an alternative can be created simply by varying the resource basis or consumption volume. However, the value chain typically responds to this with a linear correlation, so a 5% increase in flow results in a 5% increase in indicator results. An alternative can be defined, where the reaction to the increase is modelled differently by changing product shares and relative indicator values that exhibit non-linear behaviour. For example, after a certain production capacity is reached, all flow is directed to a different production system or after a certain threshold, energy efficiency significantly decreases. ToSIA typically uses a one-year time window to quantify material flows, but

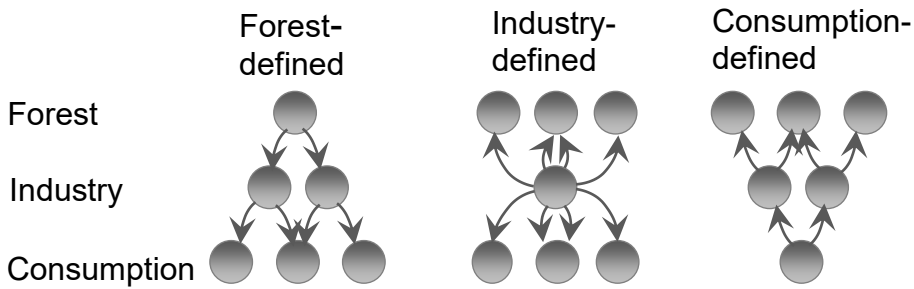


Figure 6. Alternative ways to define the focus of material flow calculation in value chains (paper III, Figure 3).

can use 5-year average flows to even out annual variation. In the case of prospective studies, baseline future projections are contrasted with projections incorporating the ex-ante “what if” question – the impact of which is to be evaluated (Arets et al. 2011). For the process selection, those parts of the value chain that do not differ between alternatives, can be covered by more aggregated processes, as they do not require the same level of detail as those where the alternatives differ from each other. Elsewhere than in the loci of differences in value chain topology or relative indicator values, the changes in indicator results mostly correlate in a linear fashion with changes of the material flow.

- ii) ***Different value chain perspectives for analysis:*** An FWC is defined from a certain viewpoint, or perspective, such as a value chain starting from the forest (growing, management options, harvesting) followed by the industry creating wood products and ending with product consumption and waste management or recycling. A value chain can be defined from different perspectives of roughly three types:
- initialization from resources (i.e. beginning);
 - initialization from a given industrial stage or operation (initialization from the middle);
 - initialization from a given consumption of a product.

In principle, a value chain could be initialized from a given amount of waste (i.e. end of the value chain). This might be useful to see what production levels would be required to obtain an adequate amount of recyclate as an input to a recycling process, to estimate whether an adequate supply of recyclate would be available to some consequent utilization.

Figure 6 illustrates some typical but abstract value chain perspectives and Figure 7 illustrates some concrete case studies (Werhahn-Mees et al. 2011b). ToSIA supports these perspectives by allowing initialization from various locations within the value chain. Initialization means giving a concrete amount of flow (e.g. hectares of forest or a national magazine paper consumption) for a process that is then used as the flow calculation basis for all consequent processes in the value chain. The two perspectives correspond roughly to defining a study based on available resources, or a given consumption. A study

based on a certain production capacity is possible by careful definition of the chain with a clear separation of the top and bottom halves, and by utilizing a combination of the two previous approaches.

b. Choosing system boundaries

- i. **What is included and what is not:** The subject of the study is a change, the sustainability impacts of which are to be analysed. On a general level it can be said that those parts of the value chain that are not directly affected by the change get less attention. Less can mean that they are included in a more aggregated form, are captured indirectly as a backpack, or are even excluded.
- ii. **Geographic boundaries:** If the focus of the case study is a specific region, the production of imported raw materials or products and the use of exported materials and products might be outside of the scope of a given study. ToSIA does not typically aim to capture the total environmental burden of a product, like the environmental product declarations (EPD) made with LCA. Looking at local environmental, economic, and social impacts is a valid context for regional decision makers (den Herder et al. 2012).
- iii. **Different system boundaries for different indicators:** System boundaries have been defined for some ToSIA indicators in the EFI Technical Report 36 (Berg 2011). Because indicators of different sustainability dimensions are assessed for the same processes in the value chain, the system boundaries are harmonized to a significant extent. In the ideal case, system boundaries for environmental, social, and economic indicators are harmonized as far as meaningful, including supply chains and indirect effects. The focus is on the effects of changes, and thus very detailed assessment of indirect effects is not always necessary. However, equal system boundaries between indicators are not always meaningful, which is the case with, for example, GHG emissions. The argument with respect to GHG emissions is that as we all share the same atmosphere – it does not

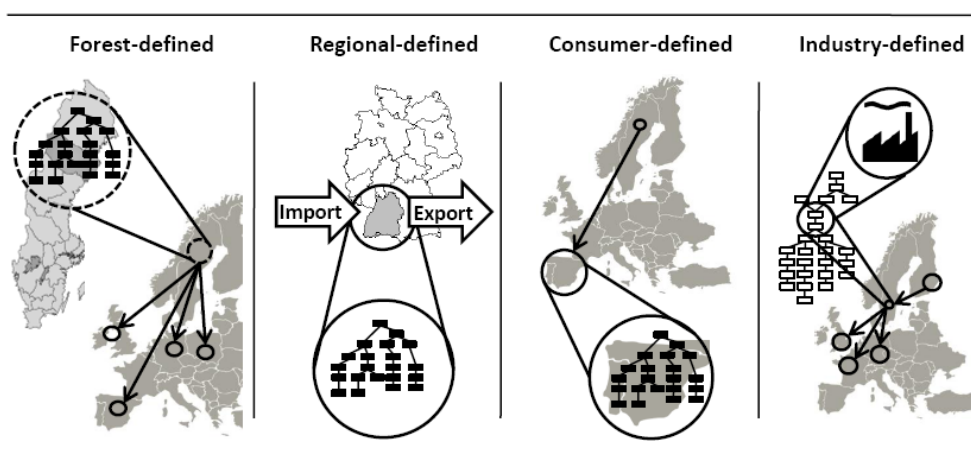


Figure 7. Value chain perspectives from case studies (Werhahn-Mees et al. 2011b).
(Figure reprinted by permission of the publisher: European Forest Institute)

matter where the emissions take place (den Herder et al. 2012). This question of indicator system boundaries can broaden the scope of the study – called “system expansion” in LCA context (Weidema 2000; Ekvall and Weidema 2004). For example, in the study of den Herder et al. (2012) the selection of indicators through consultation with stakeholders to determine relevant indicators (Haatanen et al. 2014) affected the topology design. In the den Herder et al. (2012) case study, the need to cover total GHG emissions led to including a significant part of the crude oil refining value chain, which takes place outside of the geographical system boundary set for that particular study.

2. Defining the value chain structure

- a. **Creating a chain topology:** A value chain topology is composed of interlinked processes, linked by the products flowing from one process to another (see Figure 5). A process receives a mix of products as input and produces a mix of products as output. The chapter *Topologies of value chains* gives more theoretical background on this. A topology is realized by defining the processes, the products, and connecting the processes and products to each other. The immediate purpose of the topology is to dynamically calculate material flows. For this purpose, we define input shares and output shares of products (see Figure 5), which are then used to divide the material in a process between its inputs or outputs, depending on the direction of calculation.

Much of the scoping and definition work goes hand-in-hand with drafting topologies, which aids in the thinking process by, for example, illustrating system boundaries. The definition of the concrete value chain structure is done through careful consideration of the defined “Goal and scope of the study”. Often this step is carried out iteratively, e.g. by fine tuning the system boundaries as the problem becomes more concrete through defining the topology using concrete processes and products.

- b. **Specifying processes and products:** Here we make concrete the scope of the study by defining the aggregation level and concrete content of processes. Each process needs to have a *process unit*, and *input and output products*, which in turn need their relative shares to other inputs/outputs and *conversion factors* for converting products between different units. The *product shares* give the proportion from either total input or output of an individual product into or out of a process. Typically, topology, process, and product creation are simultaneous activities.

3. Material flows

- a. **Initializing flow calculations:** The information defining flows, entered by users, is relative except for initialization values. The point in the chain where this value is given is based on the value chain perspective chosen, e.g. by giving the area of managed forests or a given consumption of a product. Several processes can be initialized, depending on the topology (Green et al. 2011). This initialization forms the basis for the calculated material flows of all other processes. This initialization can be, for example, 500 000 ha of forest or 1 000 000 tons of newsprint consumption.
- b. **Calculating material flows:** Calculation starts at the initialized processes. If a forest area is initialized at 500 000 ha, this is converted to a *base unit*, most typically tons of carbon. This amount is divided between the output products,

according to their output shares (expressed in terms of the base unit). Perhaps 1% of the total carbon will be harvested annually. This product, the one percent of wood for harvesting, is connected to the next process, harvesting, where it is an input product. Before the product is “passed on”, it is converted from the base unit to the *product unit* (e.g. m³ of wood ready for harvesting) using the *conversion factors* defined for each product. It is then passed as input to the next linked process in the chain, where the arriving input in product unit is converted to the base unit in the next process, and summed up with other inputs to form the total amount of material for this process. Input shares are not employed to restrict the amount of input accepted into a process, but they are used when the calculation proceeds in the opposite direction. For an example of flow calculation see the topology in Figure 5.

Once material flows can be calculated for the first time, errors or omissions in data are typically noticed, as inconsistencies in flow calculation are typically replicated by downstream processes, and are easy to spot. Experience has shown that it is advisable to first get the flows calculating correctly, before moving on to work with indicators, as then a miscalculated flow can be ruled out as a source of error, in validating indicator results.

4. Indicator calculation

- a. **Indicator selection:** In the EFORWOOD project, a sustainability indicator framework tailored for ToSIA was developed (Rametsteiner et al. 2008; Berg 2011; Pülzl et al. 2012), from which relevant indicators can be selected for cases studies. It is recommended to use consultation with stakeholders to determine relevant indicators (Haatanen et al. 2014). This helps to ensure that results are relevant for those interested and resources for data collection are focussed where it matters. It is rare that a study would be carried out using the full 100+ indicator set, as resources for data collection are usually limited, and feasibility of data collection can also play a key role in the indicator selection.

The relevance and consequent selection of indicators is determined by the goal setting for the case study at hand, and the scenario that is being analysed. From the point of view of highlighting trade-offs between alternatives, the selected indicators should show differences between the alternatives. As ToSIA focusses on the impacts of a change, indicators where no change between the evaluated alternatives is forecasted to take place, are not of significant interest, even if “no change” can be a positive finding. Also, if the intent is a stakeholder holder or facilitation context, then indicators that do not change, are of no use to methods such as the MCA connected to ToSIA (Prokofieva et al. 2011b; Wolfslehner et al. 2012).

- b. **Data collection:** Data sources (Figure 2) depend on the scope of the case study. Specific and empirical data can come from, for example, direct measurements or collected directly from the enterprises. Generic and derived data can be collected from, for example, literature, LCI databases, and national statistics. Estimated data can be acquired through discussion with actors or experts in the case study domain (Paper I). Data can also be obtained from models, e.g. EFISCEN (Nabuurs et al. 2001; Eggers et al. 2008) to estimate the available forest resources at some point in the future (ex-ante). The collection of data for an indicator dataset typically takes up the largest share of work in making an assessment with ToSIA. To improve the efficiency of indicator collection work,

targeted spreadsheet-based tools have been developed for automatically deriving indicator values utilizing correlations, where, for example, a major driver for indicator values is productivity of machinery. Such support tools have been developed for forest operations (Vötter 2009) and transport processes (Monnet and Le Net 2011; Chesneau et al. 2012). ToSIA also collects and displays the assumptions and other metadata used to produce a relative indicator value, such as the data source or algorithm used for producing a value. This allows a user to validate the veracity of the provided indicator values.

- c. ***Calculating indicator values for processes, value chain segments and the complete value chains:*** For most indicators, the calculated total sum of incoming flows, converted to the *process unit*, on a process level is multiplied with the relative indicator value provided, giving as a result, for example, the realized total amount of employment generated by the forest management process. These per process indicator results are then aggregated (by summing up) based on various process attributes such as country or phase of the value chain to form totals for comparison of alternatives. Some other indicators such as the share of female employees, will not get multiplied with the flow, and are aggregated using weighted averaging. Further still, for example, the indicator “total production”, which selects the volume or value of all finished products, requires customized calculation mechanisms. Also qualitative indicators are possible, but they typically do not show meaningful differences in the comparison of alternatives nor are they equally useful in MCA as quantitative indicators. The “resolution” of quantitative indicators to show change is better.

5. Value chain comparison and analysis

- a. ***Sustainability impacts of value chain alternatives:*** “The purpose of ToSIA is to analyse and assess FWC-sustainability impacts of changes in the FWCs” (Paper I). The simplest comparison needs at least a baseline and one alternative. When assessing the differences between a baseline and its alternatives, the individual processes may not match process-by-process between the alternatives, and hence aggregation of indicator results may be used by value chain segments or at a value chain level. Value chain segments in the case of forest wood chains can be, for example, “forest resources management” or “processing and manufacturing”. The direct comparison of indicators can be done as absolute or relative between alternatives: for example alternative b results in 50 person years more or a 15% increase in providing employment than the baseline.
- b. ***Evaluation of results:*** ToSIA can directly show the calculated differences in individual indicator values, in detail or aggregated from. It also allows the results to be allocated to specific products and for the selection of allocation units. However, meaningful interpretation of changes in tens of indicators covering different sustainability aspects may be difficult. To enable comparison of the calculated alternatives, in the frame of the EFORWOOD project, the coupling of three evaluation methodologies was developed to ToSIA. Multi-Criteria Analysis (MCA) can be used to give stakeholder preferences for sustainability indicators to subjectively select the most desirable alternative (Wolfslehner et al. 2011, 2012). Cost–Benefit Analysis (CBA) gives economic valuation to environmental and social externalities (Prokofieva et al. 2011a), and calculates a net present value (NPV) for the different decision alternatives

(Prokofieva and Thorsen 2011). Policy Analysis (PA) provides a comparison of the calculated indicator results to pair them with, for example, thresholds found in legislation or non-binding agreements (Vogelpohl and Rametsteiner 2011; Vogelpohl et al. 2011).

Methodological and technical details of the ToSIA methodology

Indicator definition and calculation

The original “full set” of EFORWOOD sustainability indicators with detailed specifications for their calculation can be found in the *Data Collection Protocol* (Berg 2011). Work has also been carried out in examining the use of qualitative social and cultural indicators for ToSIA in general (Edwards et al. 2011b), and specifically on the recreational use of forests (Edwards et al. 2011a, 2012b). The “full set” has been later expanded, as case studies have necessitated definition of new indicators (Tuomasjukka et al. 2013b; Berg et al. 2016). A discussion on the development of the ToSIA indicator set is given by Pülzl et al. (2012), a comparison of indicator development for SIA approaches by Rametsteiner et al. (2011a), and an overview of SIA indicators and tools for a forest-based bioeconomy by Karvonen et al. (2017).

The ToSIA sustainability indicators relate to the sum of input products to each process (material consumption), converted to the same unit. During the material flow calculation for a value chain, all the incoming material flows to a process are converted to the unit defined for reporting the indicators of the process in question. This unit (also called the reporting unit or process unit) can be freely selected for each process as appropriate for that activity (e.g. ha for forest management), but conversion factors for each product to this unit must be provided. All relative indicator values coming from the ToSIA database for this process need to be provided in relation to the selected process unit. The relative indicator unit for an employment indicator can be, for example, “person years of employment per ha of forest to be managed”. The calculated total sum of incoming flows is multiplied with the relative indicator value provided, giving as a result, for example, the realized total amount of employment generated by the forest management process. These per process indicator results can then be aggregated (e.g. by summing up) based on various process attributes such as country or phase of the value chain. Not all indicators are relative to the material flow, such as the percentage of female employees. In these cases, a weighted average is usually used for aggregating over a group of processes. Calculated indicator results aggregated to a chain level can be contrasted to results of an altered chain such as one incorporating a new bioenergy policy. Such technological, policy, or other alternative ways of operation can cause a quantified sustainability impact when compared to a status quo baseline and measured using the calculated sustainability indicators.

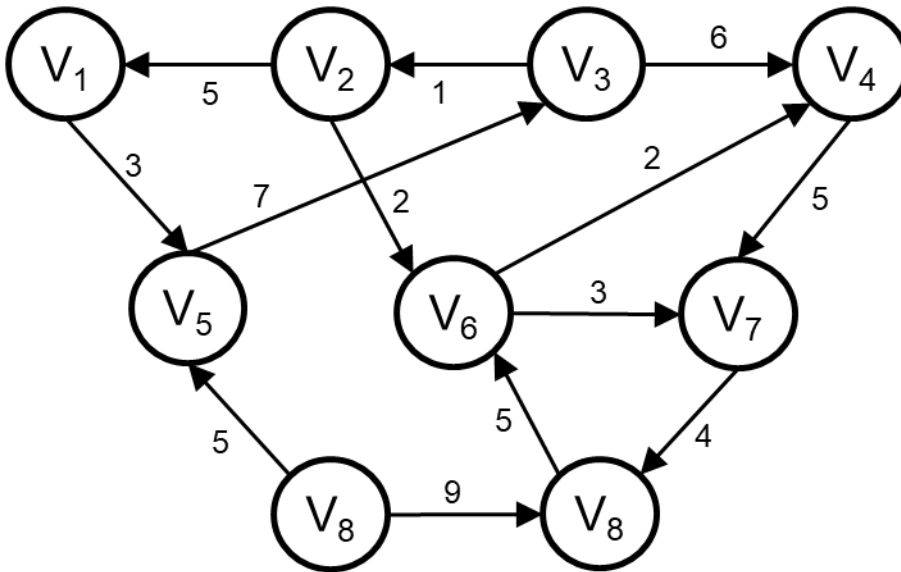


Figure 8. A weighted, directed graph.

Topologies of value chains

The structure of a value chain in ToSIA is essentially a weighted directed graph¹. A weighted directed graph is a mathematical concept, and its application in our context is a value chain. An example of a weighted directed graph is depicted in Figure 8.

Directed graphs are composed of vertices and edges. In Figure 8 the vertices are denoted by “V_n” and the edges are denoted by the arrows connecting vertices. The vertices (V) are analogous to processes in the FWC, while the arrows in this graph are edges, which are analogous to the links (product flows) between FWC processes. Figure 8 also shows weights for the edges. The amount of flow from process to process in ToSIA does not constitute a weight, but the shares defining the relative proportions of flow leaving each vertex can be seen as a weight that represents the “cost” of traversing that edge. In the FWC context, each edge has a value between 0 and 1. The weight is the fraction of input that leaves a vertex on this edge. The length of a path is determined by multiplying the costs, rather than summing up. The graph may contain cycles (loops), such as the representation of paper recycling. In Figure 9, an example of a cycle is the path: {V₁, V₅, V₃, V₂, V₁}. Examples of how a weighted directed graph is implemented as a FWC are given in Figures 5 and 10.

¹ For more information on the concept of a directed graph:
[https://en.wikipedia.org/wiki/Graph_\(discrete_mathematics\)#Directed_graph](https://en.wikipedia.org/wiki/Graph_(discrete_mathematics)#Directed_graph)

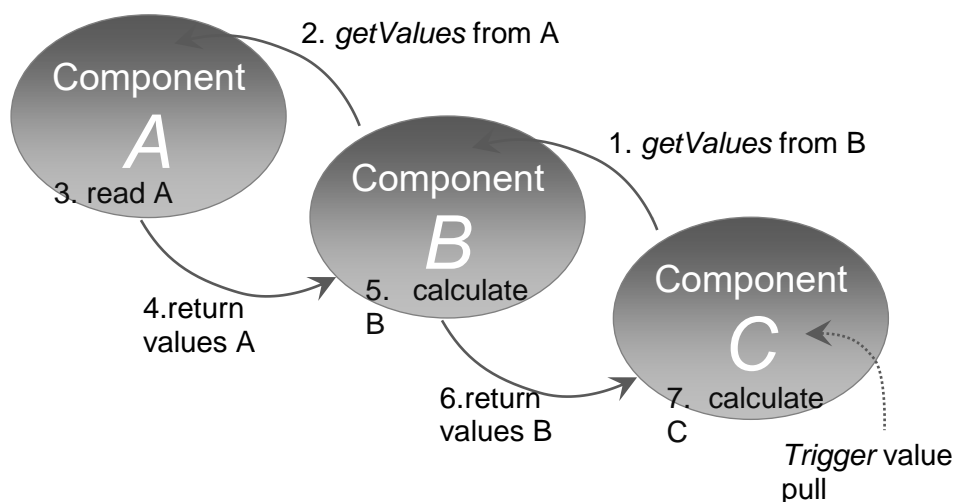


Figure 9. Chain of linked (model) components A, B and C (derived from figure 4, paper III).

Implementation of the value chain material flow calculation in ToSIA using the Open Modelling Interface (OpenMI)

Relatively early on in the development, it was decided by the ToSIA developers to take advantage of the OpenMI (Gregersen et al. 2007a) and its Java version's source code. OpenMI is utilized as the knowledge exchange mechanism between linked models, which in the case of ToSIA are the processes of the value chain. The exchanged knowledge are the volumes of product flow, flowing from process to process. It is how the material flow calculations are implemented. While in the prototypes, the flow calculation was achieved with more straightforward recursion, the advantage of OpenMI is a more standardized modular approach to treating each linkable component as autonomous black boxes. The rationalization for adopting OpenMI was that it provided ready solutions for integration of models and some reusable solutions for presenting model linkages visually. Most importantly, it was considered that "solutions implemented using standardized methods tend to have better maintainability than completely customized solutions" (Werhahn-Mees et al., 2011b). It was also thought that utilizing OpenMI in a non-hydrology application context could "give back" to the open-source platform and strengthen the case of OpenMI as a more generic model interlinkage platform (EC-JRC-IES, 2010b).

OpenMI was developed in an EU project (HarmonIT) focussing on integrated water resource management (Gregersen et al. 2007a). The application of OpenMI has been spreading to other domains of natural resource management (Verweij et al. 2007; Knapen et al. 2013). The OpenMI is a model linkage framework that enables creation of networks of interlinked models (Gregersen et al. 2007a). Dynamically linked networks of models enable the description and modelling of more complex entities or larger systems. OpenMI defines the standard *interface* that each encapsulated model needs to implement. The encapsulation can be as simple as a *wrapper* that transforms the models outputs/inputs to the format required by the interface (Gregersen et al. 2007b). This enables existing models that are able to produce required types of output/accept input to be encapsulated within a *wrapper* with

relatively small effort. The possibility to reuse *legacy code* written in programming languages such as C or Pascal, makes OpenMI a powerful platform for pooling together large existing bodies of work, without a need to invest in their redevelopment (Gregersen et al. 2007a). 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* (Gregersen et al. 2007b). These *exchange items* can be linked to each other with *links*. The original hydrological modelling domain is reflected in the interlinkage structure, as the linked *exchange items* have a time and spatial dimension – what is exchanged, how much, when, and where – necessities when needing to express flows of water. A collection of linked *linkable components* is called a *composition* (OpenMI Association 2010). OpenMI provides a means 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 the exchange of results is implemented between models in OpenMI is demonstrated in Figure 9. The pull to the values of component C triggers it to request the values of component B (see 1) to enable C’s calculation. B depends on A consequently requesting values from A (see 2). Component A has a value defined, for example in a database (3), returned the value to B (4) allowing B to perform its calculation (5), then results from B are passed on to C (6) to produce the values originally requested (7).

The calculation of material flows is therefore 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. Another necessary condition for calculation is that all “top” processes should be initialized.

Calculation of cyclic material flows (loops)

Material flows are analysed using a topology. ToSIA must be able to perform calculations for a wide range of potential topologies, restricted only by the user’s creative capacity. De facto, most chains have a “tree-like” topology, but they may also contain loops. Calculation of flows through loops is needed especially in modelling recycling of raw material and reuse of products.

ToSIA calculates material flows of chains containing loop structures within a reasonable accuracy, as long as a non-infinity solution exists. By iterating through a loop a given number of times, the solution is approximated. Accuracy depends on the number of iterations calculated. As long as the series is convergent, the sum of a mathematical series approaches a certain value (limit) (see e.g. Harkness and Morley, 1893; Lahtinen and Pehkonen, 1994). The sum of a series that is not converging, but diverging, is infinity. The accuracy of calculating a sum of a series through iteration also depends on how “fast” the series approaches its limit. The precondition for the mathematical series to be convergent in our case is in the topology of a loop. A loop must have at least one “sink” – a vertex with an edge leaving the loop with some weight on it. The used calculation approach assumes that there are no unaccounted material losses along the flow (i.e. all materials coming to a vertex leave that vertex). However, such a case would still calculate correctly because the lost material would form a “hidden sink” as a loss is reflected in that 100% of input does not exit a vertex.

A situation that may not occur, is that the sum of weights for edges leaving the loop may not be more than 1.0, meaning that there is no additional input to the loop from a process; a process in a loop may not output more than the sum of its inputs. An example of a loop is shown in Figure 10 between the processes “Pleasure boating” and “Annual maintenance of sailing boat”. A part of the output (used boats) of “Pleasure boating” goes as input to maintenance, and all maintained boats go back as input to pleasure boating. The production capacity for making new boats may be quite small compared to the number of boats in use. As the share of boats removed from use determines the number of boats in circulation, the amount of boats in use is primarily determined by how well the owners take care of their boats. ToSIA describes an equilibrium situation, not a situation where, for example, the number of boats in use would still be growing. Consequently, ToSIA does not model accumulation of pools or stocks of products that are caused by changes in production or consumption volumes over time.

An FWC in ToSIA is a weighted directed graph, where each edge has an assigned value of $p \in (0,1]$. The weight is the fraction of input that leaves a vertex on this edge. Taking into account the assumptions above, we must define that for a given vertex: $\sum_{e \in E} p_e = 1.0$, where E is set of edges leaving the vertex. If we have a loop (size n) in a graph, we can develop the formula for calculation of flow for any vertex of the loop (see Appendix 1):

$$X_i = \frac{1}{1-P} \times \sum_{j=1}^n I_j \times P_{ji} \quad (1)$$

Where:

X_i - total flow through the vertex

I_j - “external” input to the loop into vertex j

$P_{ji} = \prod_{k=j}^i p_k$ - “Path weight from j to i” – product of weights of edges connecting vertices j and i

$P = \prod_{k=0}^n p_k$ - “Loop path weight” – product of weights of all edges of the loop

From this formula we can derive a few key consequences:

1. A necessary condition for the loop being calculated: the flow in a loop can be calculated if the loop has at least one “sink” ($|P| \neq 1$)
2. For the calculation of the loop we use a well-known approximation (with precision $\rho \sim P^{m+1}$) by geometric series:

$$X_i \approx M_i \times \sum_{k=0}^m P^k \quad (2)$$

Where:

m is the number of iterations

$$M_i = \sum_{j=1}^n I_j \times P_{ji}$$

The amount in a loop can be at a state of equilibrium only when the input to the loop equals the output from it. Formula 1 gives the proof of the statement: total amount to the sink from the loop is equal to the total external input to the loop (see Appendix 1).

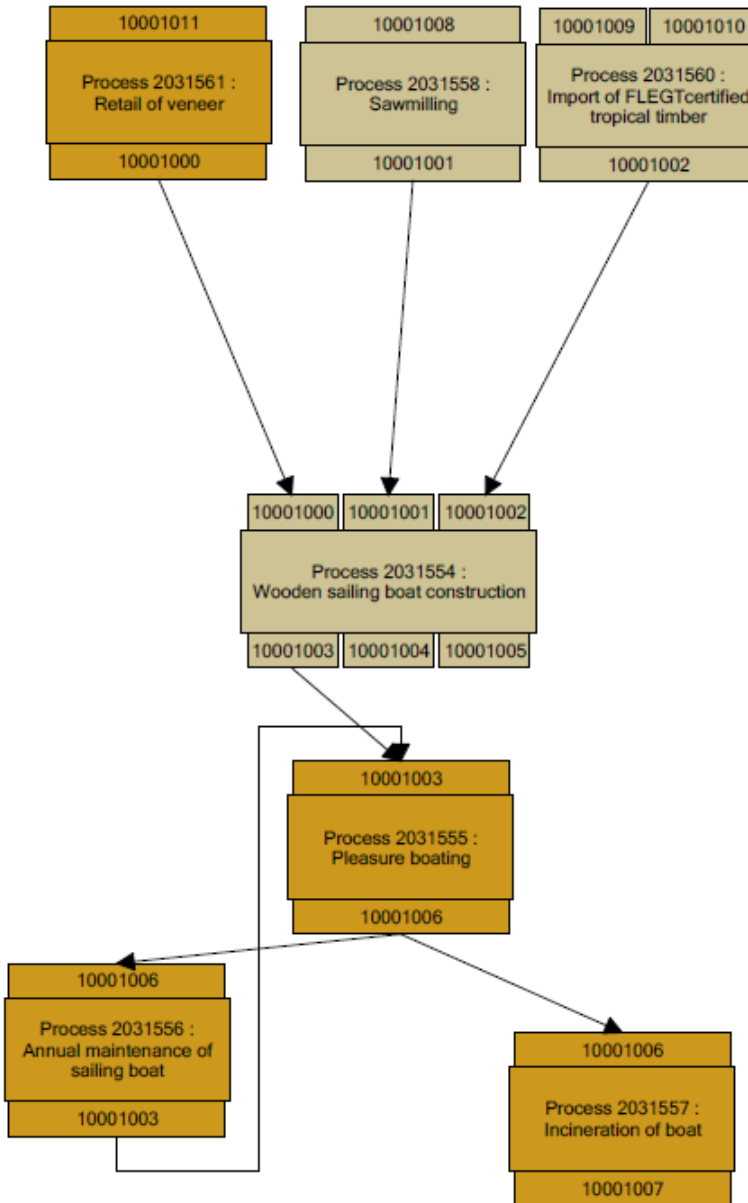


Figure 10. Example of a simple loop in a value chain (paper III, Figure 9).

The OpenMI version 1.4 (Java) does not provide explicit support for a model to “follow” the situation of calculation in a composition. According to a “black box” approach, a component is not aware of its context. Along these lines, OpenMI is not equipped to analyse topologies with respect to whether they contain loops. OpenMI documentation mentions a class named “Iteration controller” (package advanced control) and instructs it to be used in

cases of “bidirectional” linkage between components (Sinding et al. 2005). These bidirectional linkages are simple loops between two components. Unfortunately, the package advanced control is not available in the OpenMI version 1.4 (Java). To perform the iteration algorithm for calculation of flows in loops, some functionality of the Iteration controller was introduced for ToSIA in a class inherited from the OpenMI *linkable component*. The ToSIA loop calculation approach uses the information on how many times `getValues` (see Figure 9) has been called on a specific instance of linkable component, in order to be able to determine if it is located inside a loop. Together with a maximum number of iterations, the information on iteration count can be used to break the otherwise perpetual recursive calls inside the loop and begin returning results. This functionality limits the deepness of recursion in `getValues` method, and thus prevents problems associated with eternal recursion, the practical consequence being application termination due to running out of memory.

An end-user has the freedom to define a chain topology without restrictions, but the downside is the possibility of introducing erroneous definitions. The limit on the number of iterations that a loop can perform negates the problem of eternal recursion in flow calculation, but the user can define a loop structure that creates an expanding series. In this case, the calculation result will only result in such a large calculated flow that a savvy user can understand the problem. The earlier prototypes of ToSIA implemented loops in such a fashion, that they were iterated until the calculation result stabilizes to a value within a given accuracy. However, such behaviour could calculate loops consisting of expanding series continuing until the system memory is exhausted (typically the call stack memory runs out first) which causes the application to terminate operation without completing its objective. Therefore, the approach using limited iterations described at the beginning of this chapter was adopted. Our temporal system boundary is one calendar year. The iterations reflect the amount of material remaining in the production loop from the previous years of virgin raw material use. The current solution has proven to be very scalable and able to handle large compositions – the largest one so far has been an EU-scale FWC (Lindner et al. 2012) with nearly 2200 linkable components and over 10 000 links, which, as far as the author knows, is an OpenMI record.

ToSIA Software development

The ToSIA architecture has evolved over time considerably. It has gone from a prototype with application logic only, to a suite of linked tools with separate user interfaces for designing chains, running calculations, and evaluating the results. A brief overview of the development is given below.

Prototypes

The first prototypes served as a calculation proof-of-concept, to show that chain topologies can be correctly calculated and loops can be handled. The prototypes were Java programs that read XML input files. They were used by a command-line interface and did not take advantage of OpenMI. Java was chosen from the start as the implementation language of ToSIA, as a single version of a program 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.

Version 1

For the version 1 of ToSIA (Werhahn-Mees et al. 2011b), a Java Swing based graphical user interface (GUI) was constructed and OpenMI version 1.4 was adopted for the value chain flow calculation (OpenMI 1.4 was the version available at the time of implementation). The part of ToSIA that calculates and displays results was only a part of the toolbox developed. For version 1, the EFORWOOD databases, database client and application server were implemented with MS Access and Delphi (some of these components are shown in Figure 2), initially to facilitate the data collection in EFORWOOD (Institute of Forest Ecosystem Research 2011). These components evolved to play a central role in carrying out case studies, as a large share of that work is related to defining value chains and collecting and entering data (just like LCI is the largest share of work in carrying out an LCA study) (EC-JRC-IES 2010b). The value chains and attached data are transferred for calculation to ToSIA by exporting the selected value chains from the EFORWOOD database client, and consequently loading these in ToSIA. The use of the EFORWOOD database client requires a constant internet connection, sensitive to network breaks, but the exported XML files could be taken “to go” and run at any later point in time. ToSIA can export its aggregated results as an XML file, for further analysis, e.g. to the integrated MCA module.

Version 2

ToSIA version 2 did not include significant changes to the software architecture, but dealt with trying to generalize the method from topical constraints originating from the purely forest-based sector EFORWOOD. The database was moved from its original developers to be hosted at EFI (the TMUG coordinator). The ToSIA Management and User Group (TMUG) was prepared and launched, which aims at managing, disseminating, and promoting ToSIA work and development. The software was also internationalized and the user interface of ToSIA, CBA, and MCA tools were translated to Finnish and Swedish for the benefit of regional stakeholders. The interface for exporting XML results from ToSIA to MCA was amended to remove non-dynamic attributes, and provide them dynamically instead. The database related tools were renamed as the: ToSIA Database Client, ToSIA Application Server, and ToSIA Database(s).

Version 3

The MS Access version of the EFORWOOD database ran into the constraint that the technology permitted only eight concurrent users and did not allow database files larger than 2GB. The limit on the number of concurrent users became a bottleneck, especially in a training or stakeholder workshop context. The database technology was therefore changed to MySQL to overcome this restriction. At this point, it became necessary to update the code of the ToSIA database client and application server from Delphi 6 to Delphi XE (XE4 was chosen) as by this point Delphi 6 had become obsolete and Delphi XE was required to support the connection to a MySQL database. “The new version of Delphi came with substantial changes in core technologies used by the ToSIA database client and the ToSIA application server (client/server communication, Unicode support, etc.) which required many changes in the source code” (Tuomasjukka et al. 2013b). The usability of the ToSIA database client was also improved (e.g. by adding a data entry wizard that allowed bulk data upload), liberating users from having to tediously enter all data one by one using the database client.

Version 4

The technical problems of ToSIA database client and the databases that were brought on by the initial design, were resolved in ToSIA version 3, by changing the database technology, and by significant updates to the database client software. While the database technology migration was successful, the database client update was not able to solve some reoccurring problems. The result was a highly unstable system which was unusable for the purpose that it was designed for. Constant problems with the reliability of the updated database client led to the reimplementaion of the ToSIA database client in Java (JavaFX GUI), which was also expected to improve the present compatibility and enable future integration of the ToSIA database client and ToSIA engine (Verkerk et al. 2016a). The reimplementaion also included a new procedure to directly load data from the ToSIA database into ToSIA. The old (since ToSIA version 1.0) procedure of manually exporting chain and process .xml files from the ToSIA database client (Figure 2) and new direct loading procedure (Figure 11) are both still in use.

A significant technical design change was also made, where the database design is now created and managed based on the ToSIA database client's object structure. The technology employed here is called Hibernate Object Relational Mapping (Hibernate ORM or commonly just Hibernate). Hibernate provides a framework for mapping a Java object model to a relational database, which it does by mapping from Java classes to database tables, and mapping from Java data types to SQL data types. This significant technology change relieves the developers from managing the database structure as this is "outsourced to Hibernate", but causes challenges in porting existing data from one database design to another as the Java object model changes.

Hibernate was first implemented in the database client, but it quickly became apparent that such a solution was not feasible due to unacceptable performance. The client is located on a user's computer, while the database is on a server. The excessive communication of Hibernate through a firewall with a server is exorbitantly slow. The only workable solution found, while still keeping Hibernate, was to expunge the Hibernate-database communication from the database client to the database server software. The communication between the client and server software is now carried out more sparingly using JSON.

Version 5

The last technical updates to ToSIA have not been subject to publication anywhere as of 2021. The complete reimplementaion of the database client has left still a lot of reliability and quality improvements to be made, which have been incorporated into the next major release. Significant architectural changes were made to this version of ToSIA, where the independent Java Swing user interface of the ToSIA engine that had been appended with Java FX over time was dropped, and the ToSIA engine was integrated with the ToSIA database client. For the first time, a released version is able to show visually calculation results, i.e. the calculated flows and indicators in context of the same value chain topology the user has designed in the database client. This change considerably improves both usability and the productivity of working with ToSIA.

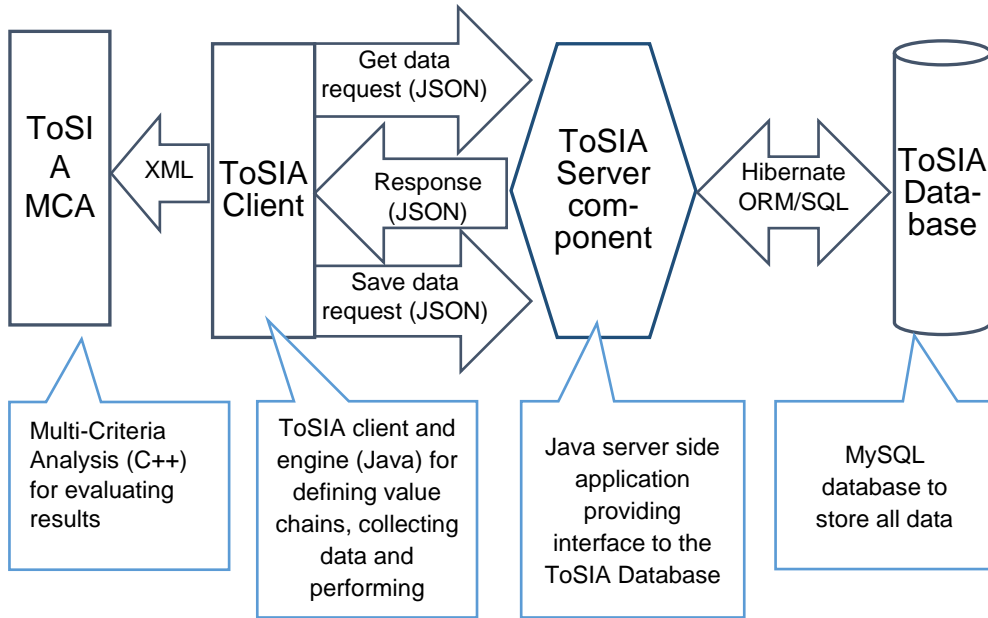


Figure 11. ToSIA software architecture (v5).

Software architecture at present version (v5)

ToSIA architecture presently consists of the ToSIA database, ToSIA server application and the ToSIA client application (see Figure 11). The server software improves security by preventing unauthorized access and makes data processing between the client and the database more efficient. The server and client communicate in JSON and the server-database communication takes place with Hibernate ORM. The client is used for designing value chains, entering data, performing the calculations, and presenting the results. The database is MySQL. The ToSIA client and server are implemented in the Java programming language. The client continues to take advantage of the OpenMI version 1.4 (Java) for material flow calculation.

Integration of decision support modules to ToSIA

ToSIA's calculated indicator impacts are offered as a data source for further analysis to MCA, CBA, PA, or any other methodology capable of being adapted to utilize the quantified impacts from ToSIA. The linked MCA module is implemented in C++, and results from the Java-based ToSIA are transferred to MCA using an .xml file. The MCA is currently compiled only for Windows based operating systems. The CBA module is embedded into the ToSIA versions 1 to 4, implemented in Java with a Swing GUI, and reads the ToSIA calculation results directly from ToSIA's internal data structures. Additionally it reads in the economic valuation of non-economic indicators (externalities) from its own .xml files (Prokofieva et

al. 2011a). The CBA implementation was not ported to ToSIA version 5 when the Swing GUI was dropped, due to limited resources. The implementation of the coupling of the PA module is the simplest by design – a link to the online PA database’s web user interface, even if a slightly more detailed interface was initially planned (Vogelpohl and Rametsteiner 2011).

APPLICATIONS

Application on cascading value chains – trade-offs in sustainability impacts of introducing cascade use of wood (RQ2, RQ3 paper II)

According to the categorization provided at the beginning of the previous chapter (The Design of ToSIA), cascade use is thematically located between straightforward value chains, and truly cyclic ones. In non-technical discourse, cascading and cyclic value chains are often equated as strategies for resource efficiency in a circular economy (Sirkin and ten Houten 1994). From a modelling perspective, cascading value chains are simply regular value chains, albeit longer, but differ in that the initial raw material changes form and becomes several end products during its lifetime. This poses challenges for allocation, which were not addressed in “the allocation paper” (paper IV), but are discussed later (see Discussion).

The study in paper II, analysed the ex-ante sustainability impacts (RQ3) of shifting material from energy use to material use by adding cascaded wood into the production of wood products. This increase is further divided into four alternatives: (1) the cascaded input replaces virgin resources, which results in a decreased need for resources; (2) the cascaded input replaces virgin resources, and the freed virgin resources are used for energy production; (3) the cascaded input supplements virgin resources, and a larger production volume is achieved, and the increase is exported; and (4) the cascaded input supplements virgin resources, and a larger production volume is achieved, and the increase is used domestically. These cascade use alternatives are compared to the non-cascade use practice in particleboard production within the province of North Karelia, Finland. “Direct impacts are captured using sustainability indicators representing environmental, economic, and social aspects of sustainability. Results show that introducing cascaded wood can increase carbon storage in wood products, employment, and production costs. Energy use and GHG emissions increase as well when the total wood-based industrial activity during the lifetime of wood increases” (not accounting for substitution of non-wood materials). “We conclude that cascade use can improve resource efficiency as it enables the use of wood multiple times before combustion; however, the amount of waste wood for energy generation decreases locally, and alternative sources of energy need to be identified” (paper II).

While the topic of trade-offs that occur from increasing cascade is veering off from the main topic of ToSIA method development, this particular example serves to showcase the utility of the approach in analysing complex what-if questions (ex-ante assessment, RQ2). In the assessment of sustainability trade-offs (RQ3), we arrive at the central role of substitution and the importance of both geographical as well as system boundaries. In paper II, the observations are more specific to circumstances, but at a more generic level, a few resulting “ifs” are highlighted:

- 1) If we increase the allocation of recycled wood from energy to material use, it may result in a decrease of renewable energy production, unless the lost material is substituted, e.g. by increased energy wood harvests. When the material product passes its half-life,

statistically, its embodied material becomes available again for reuse (as energy or another material product).

- 2) If the consequence of increasing the use of recycled wood is that more (virgin) energy wood is harvested and used for energy to substitute the loss of recycled wood available for energy generation – what is the benefit?
- 3) If the recycled wood substitutes virgin residues in material production and production levels remain constant, as the use of residues are not the driver for harvesting wood (but e.g. demand for sawn wood), this simply frees up the resources for a different use – and if this use is energy production – what do we achieve?
- 4) If the recycled wood is used to increase production, and this implies an increase in the total production of this product, environmental benefits may be gained in, for example, increased carbon stock by substituting mineral resources with renewable ones and avoided mining of mineral resources. Social and economic indicators may not follow this pattern, if, for example, employment shifts from producing plasterboard wall elements to particleboard wall elements, the sum of economic or social impacts may be negligible.
- 5) Local and global effects differ. If production shifts location, e.g. employment increases at one locality and decreases at another one. For local and national policy making, this is naturally a vital question. The total employment at global level might remain the same. Recovered wood previously used for bioenergy at one locality, gets now incorporated into a new product, is exported, and at end of life at the locality of its destination of export, this wood becomes available for energy generation. Global affects in, for example, carbon sequestration might be positive in switching from mineral to renewable resources, but increased production increases impacts, and should be contrasted with what is being substituted.

Paper II shows how ToSIA can be used to highlight quantified sustainability trade-offs, with a case-study example. It answers multiple points from the research questions posed in the *Introduction*. With ToSIA's value chain approach, concrete figures can be given to the trade-offs, but even more valuable is the possibility to identify and discuss the meaningfulness of these trade-offs in a complex production environment (stakeholder interaction). In turn, this enables the discovery of options with the most favourable trade-offs.

Considerations for modelling circular value chains (RQ3, paper III)

ToSIA must be able to perform calculations for a wide range of chain topologies so that the users can freely create topologies to describe their case studies. Value chains may contain loops such as the simplified example in Figure 10, which according to the categorization given at the beginning of the previous chapter, is from a calculation point of view the most complex case (category 3). Loops are used especially in modelling recycling of raw material and reuse of products, which is very relevant in, for example, assessing the effects of increased circularity. It also allows modelling of the ratio of virgin input material to the total production volume and how much recycled material a specific production system can deliver, e.g. as input to another production system. From this, we can see that the sinks of cycles can also provide raw material to a different use – so cycles can form a part of cascading value

chains, such as the non-reusable/non-recyclable fraction directed to bioenergy use (papers II and III).

In Figure 12, we show an excerpt of a more typical and realistic value chain in more detail. The example here is one country (Latvia) cropped from the EU-wide forest-wood chain (Lindner et al. 2012). Here, a cyclic part is found where material from the process “Recovery logistics (collection and sorting)” has its output “used fibre products to recycling” used as an input to a pulp mill. So already in this national value chain, the cycle is a minor part of a bigger whole. As can be seen from Figure 12, from the recovered fibres, under 50% gets recycled. This increases both the volume of the pulp production, as well as the amount of consecutive products until recovery logistics. The situation in Figure 12 is not as “clean” as in the simplified Figure 10, as pulp and paper products that are exported, fall out of recycling, thereby decreasing availability of material to recycling, leading to increased use of virgin resources – as demonstrated in papers II and III. Exports could naturally be supplanted by imported pulp and paper products that become available for domestic recycling after end of life. However, it is typical that heavily forested countries are net exporters, while their less forested trade partners are net importers. The larger EU-FWC captured this inter-European trade (Lindner et al. 2012), and while this naturally also forms feedback loops, the complexity of this value chain forced a proxy solution, where trade flows were provided less dynamically.

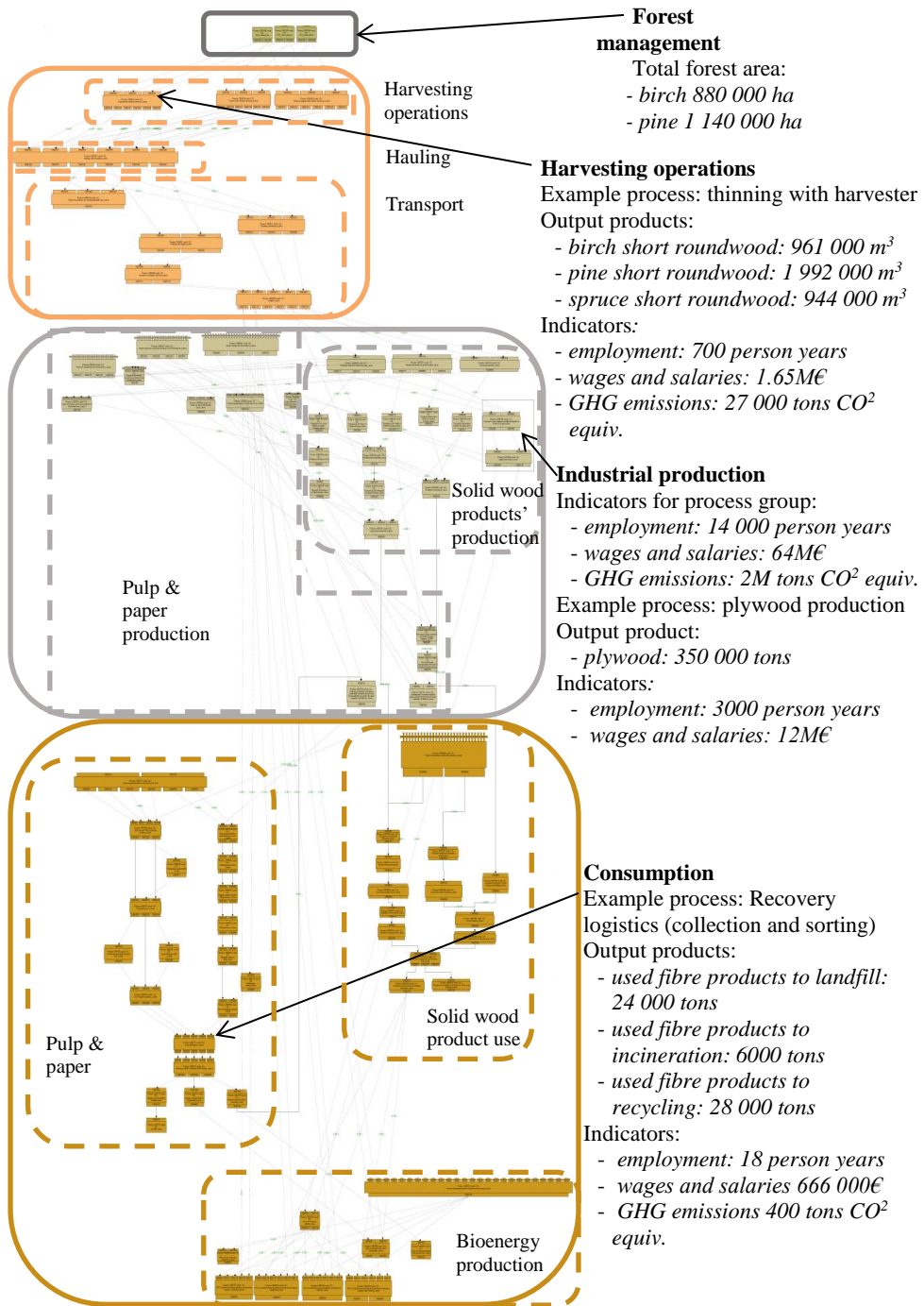


Figure 12. A general view of a sample FWC representing wood-product flows in Latvia (paper III, Figure 7). The figure shows a grouping of the processes by the phase of the value chain, and by topical groups inside those phases. The figure gives examples of some calculated indicators at process and process group level. The detailed texts are purposefully

Assigning ToSIA results to products of a forest-wood-chain (RQ4, paper IV)

The method for allocating impacts (or sustainability indicators) on a value chain without cascading would be otherwise straightforward, if it were not for multifunctional processes that produce several raw/processed materials or final products. Further insights beyond paper IV can be found in the discussion of this thesis. Allocation in multifunctional value chains was the topic of paper IV, where a method was developed that allows utilization of any allocation criteria (e.g. weight, volume, or value), or a combination of them, to determine how much (in the chosen criteria) of a given raw material in each process along a value chain ends up in a chosen end-product. This gives for each process along a value chain a share of its impacts that can be assigned to the chosen end-product. The process level indicator results can be summed up over the whole value chain to obtain a total impact for that product, which is a fraction of the total impacts of the entire multifunctional value chain. These fractions calculated by value vs. mass typically differ significantly, as illustrated in Figure 13.

There are some special cases where this logic of flow-based allocation might not hold, so results of automated allocation should be checked. Such a case can be, for example, pre-commercial thinning in a forest, depending on how the topology is made. If the input to the process is “trees to be thinned”, and the output product is “the cut of small-dimension stems”, often left in the stand, then the process of pre-commercial thinning does not “touch” the material flow that is the forest that continues to mature. The result is that none of the impacts would be assigned to the products eventually made from the wood harvested from the mature stand. While the material removed by the pre-commercial thinning does not end up in the final product, the functional purpose of the pre-commercial thinning is to improve the quality of the wood that remains in the stand, and thus purely benefits the wood that is not touched by the operation. In such cases, impacts need to be allocated manually after the automated allocation process. This particular case is found in the value chain of paper IV (Figure 2).

In paper II, the point is made that a by-product such as sawdust is not the driver of, for example, harvesting and sawmilling, and as such, a decrease in the consumption of sawdust is not likely to affect the amount of wood sawn. The industry often argues that by-products should not be given a “sustainability backpack”, as they are essentially waste, the production of which is not the economic purpose of the process. In our allocation procedure this would

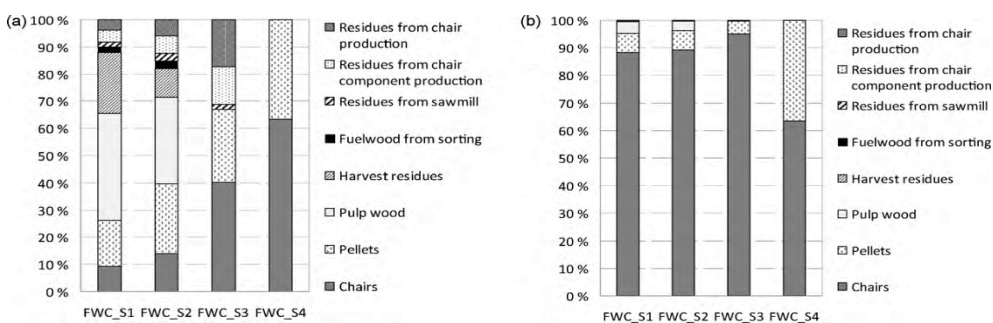


Figure 13. (Paper IV, Figure 7) The difference in results that the choice of allocation criteria makes, can be significant – (a) carbon mass based allocation, (b) monetary value based allocation of production costs to different intermediate/end-products. (Figure originally published by Palosuo (2010). *Ecol Modell* 221:2215–2225.)

be accomplished by using an economic allocation criterion, and setting the value of sawdust at 0€.

To keep the allocation relatively simple and communicable, the developed allocation applies the same criterion to all processes in the entire value chain. Aggregation of processes, which is normal practice, can sometimes cause errors in allocation. For example, a sawmilling process gets roundwood as input and gives sawn timber, sawdust and wood chips as its outputs. This process incorporates drying of sawnwood, and will allocate a share of the energy used for drying sawnwood to the sawdust and wood chips from sawmilling (which are not dried). This might not be a problem for all indicators, as drying is not labour intensive, a similar error will not be caused for an employment indicator. If better allocation resolution is desired, the process must be divided into less aggregated sub-processes, to eliminate this problem. In the present implementation of the allocation in ToSIA, the same allocation principle is used for all processes and it is also applied for all indicators.

DISCUSSION

The development of ToSIA was motivated by the identified gap in policy support tools. The EU Strategy for Sustainable Development (European Commission, 2001) voiced the need to look at how EU policies contribute to sustainable development and consequently the EU committed to perform impact assessments of all proposed major policies (European Commission, 2002). These EU policies created a demand for ex-ante impact assessment of policies to be introduced. While methods such as LCA and MFA already existed, none of the existing methodologies could provide for an ex-ante assessment, covering all different phases of a value chain from cradle-to-grave and including the three pillars of sustainability. Despite the calls for more LCSA studies, even today LCSA case studies are less common than LCA studies. There is a lack of available data (unlike the well-stocked environmental LCI databases) for the social and economic dimensions (Karvonen et al. 2018) and another shortcoming is in harmonizing the system boundaries for the different sustainability dimensions. Consequently, there was a need to go beyond present methods and develop an approach that matched the stated policy need. The topical context for the development of this generally applicable approach is the forest-based sector.

This thesis has shown the developed system from different perspectives: a *method*, a *methodology*: a *framework*. ToSIA is the first implementation of a method that combines material flow based value chain analysis with indicators of different sustainability dimensions. The thesis has shown examples of its application on value chains of categories 1–3 and presented an allocation method that takes advantage of the value chain topologies and enables allocation using various criteria. The research questions posed in the *Introduction* have been addressed and below we delve into these questions beyond the content of the papers included in this thesis and give additional context through ToSIA applications. This provides an overview of the developed method's applicability and robustness.

Combining material flow calculation with three-dimensional sustainability indicators

The first research question (RQ1) addressed combining MFA and three-dimensional sustainability indicators with consistent system boundaries to assess sustainability impacts of

changes in value chains. To validate the usability of the developed method and tool, ToSIA has been applied in case studies at various scales, focussing on comparison of alternatives. The case studies carried out over time have also served to develop application practices for the tool, and to improve both the methodology and the usability of the tool. The case studies will be addressed later in this discussion.

One of the most central and recurring discussion topics has been the nature of the implemented analysis: what is comparable, under which conditions, and how far should system expansion (Ekvall and Weidema 2004) be performed? System expansion is the practice of expanding the scope of the initial analysis to cover everything (down the supply chain) that could affect the outcome of the analysis. Just like it is possible with LCA (Nakatani 2014), with ToSIA we often simplify system expansion by being oriented at comparisons – focussing on the impacts of a change – and the things that do change. ToSIA does not attempt to give a definitive answer as to whether any given situation or practice is sustainable in itself, but rather it tries to quantify the vector of change toward a more sustainable situation or away from it (Haberl et al. 2004). In fact, Sala et al. (2015) argue that an improvement in sustainability is no indication at all that the improved situation is the least bit sustainable. ToSIA shows the calculated differences in individual indicator results between alternatives, the vector of change. It also allows assignment and allocation of a fraction of the indicator results to specific products. This is still in line with the previous idea – it does not show whether something is sustainable or preferable. Aggregation of an indicator over many processes in ToSIA does not mean aggregation across different indicators. How do you aggregate the percentage of female employment with GHG emissions and with investment costs? The meaningful interpretation of changes in tens of indicators covering different sustainability aspects can be difficult. LCA aggregates different indicators into so-called impact categories (e.g. ISO 2006; Wolf et al. 2012) such as climate change, ozone depletion, or human toxicity, in a standardized way. LCA can be used as a basis for even further aggregated indices such as the Eco-indicator 99 (Goedkoop and Spriensma 2000), which through an intricate process including weighting effects on human health and ecosystem quality, aggregates numerous indicators down into a single eco-indicator value for materials and processes. These eco-indicator values enable “designers to perform their own LCA analysis in a matter of minutes” (Goedkoop and Spriensma 2000). ToSIA itself does not aggregate over different indicators, but presents the calculated indicator results for further processing.

The issue of comparability was raised by industrial stakeholders in the EFORWOOD project that initiated the ToSIA development. The argument was that fundamentally different things should not be compared to each other with simplistic metrics. The example of Nordic long-rotation spruce/pine forestry vs. Portuguese short-rotation coppice plantations of eucalypt are not comparable systems, e.g. due to entirely different environmental conditions. Both areas surely need to maintain forests and forestry. Wouldn't it be fairer to compare alternatives within regions with similar environmental conditions? Such a comparison is admittedly more likely to result in actionable improvements within that context. However, one of the most visible topics of public debate is whether a particular source of raw material is from sustainably managed sources or not. The western public view is that, for example, palm oil from Indonesia or beef from Brazil should be avoided entirely as both cause deforestation and result in significant habitat loss and are disastrous to climate change mitigation. Meanwhile, less attention is given to the fact that the countries with the protesting consumers might have cleared their forest for agriculture hundreds of years ago – it is always easier to point the finger elsewhere. The consumption-focussed (see Figure 7) EFORWOOD

case study in the Iberian Peninsula looked at wood products consumed in Iberia, and the wood supply from forest resources locally and in south-west France and Scandinavia (Lindner et al. 2012). Given the above stakeholder concerns, the focus of the study was on the impacts of consumption changes, not on the comparison of the use of the different forest resources. Whether or not we entirely agree with the above, these stakeholder views influenced the tool development and practice so that in ToSIA comparisons are predominantly made within a value chain by looking at changes within a context where comparability remains meaningful. The question of “what is inherently comparable” has been intensely debated. The fact that a value chain and its processes form the basis of an impact assessment is also a mechanism for harmonizing the comparability of the different sustainability dimensions and indicators. All indicators will need to describe the same processes along the value chain, even if some processes may be “turned off” by not directing any material flow to them.

A long-standing ambition with ToSIA practitioners has been to carry out methodological comparison studies to see the differences in results between ToSIA and LC(S)A. To date, two such studies have been carried out. Karvonen et al. (2018) compared ToSIA and LCA results in showing the environmental benefits of integrating a pyrolysis plant with an existing combined heat and power plant. The study by Karvonen et al. was somewhat handicapped as a method comparison, as it was limited only to the environmental sustainability dimension. The ToSIA approach was used as a frame for the LCI phase of the study, which served to harmonize the setup of the study between the two approaches. LCA was then appended by LCI database data on indirect impacts. While inclusion of the indirect impacts for LCA increased absolute results, there were relatively small differences in the percentage changes between the alternatives compared in the study. In the end, the results were similar enough that the conclusions from results of both methods were the same. Karvonen et al. also deliver a methodological comparison between ToSIA and LCA, e.g. highlighting the difficulty of combining the environmental LCA’s inclusion of indirect impacts with an equal depth of analysis for social and economic dimensions. ToSIA avoids this issue by primarily focussing on the direct impacts. The other study by Tuomasjukka et al. (2017) used a renewable energy value chain to compare three different methods for sustainability impact assessment. The case study was analysed with ToSIA, LCA, and Emission Saving Criteria (ESC) (European Parliament 2009; Tuomasjukka et al. 2017), so that with ToSIA only direct impacts were considered while with LCA indirect impacts were partially covered as for many indirect impacts data was not available. The ESC mostly serves to provide points of comparison to fossil alternatives. The ToSIA indicators were adapted for better comparability with LCA and ESC. As a conclusion, SIA methods were advocated for comparisons and the joint use of ToSIA and LCA was recommended for highlighting the effects of individual value chain processes and inclusion of indirect impacts. Adaption of ToSIA indicators for LCA is not enough for comprehensive non-comparative environmental product declarations (EPDs) conforming to ISO 14040 (ISO 2006). However, a lack of availability of detailed data is a common problem for the resource supply and is an issue for detailed LCA.

Tuomasjukka et al. (2018) followed up on the Tuomasjukka et al. (2017) paper and repeated this method threesome for assessing a more complex case study comparison of technological solutions for increasing forest biomass feedstock supply “to quantify the impact of the technology choice and also the effect of the choice of assessment method”. The refined conclusions from this second effort was the recommendation to not rely only on stand-alone values but attempt to quantify both direct and indirect impacts, as their separation

was shown to reveal the “assumptions of indirect impacts included in LCA methods and the magnitude of those” (Tuomasjukka et al. 2018).

Carrying out ex-ante sustainability impact assessment and analysing sustainability trade-offs

The second research question (RQ2) asked, how the method can be used to perform ex-ante sustainability assessment or highlight sustainability trade-offs between alternative technologies and policies. To carry out ex-ante analysis, ToSIA uses the present-day situation as a starting point, a baseline. Alternative futures are characterized using future development scenarios, such as the IPCC A1, B2 (IPCC 2000). For the forest sector, the economic development in such future scenarios are converted to demands for forest products with models such as the global forest sector model EFI-GTM (Kallio et al. 2004; Moiseyev et al. 2011). This can be complemented with forecasts on the availability of harvestable forest resources in different areas with models such as European Forest Information Scenario model EFISCEN (Nabuurs et al. 2000; Schelhaas et al. 2007; Verkerk et al. 2016b). Now we have a reference future to work with, so that when we next create the alternative containing our ex-ante question, we can compare the effect of just the question, by eliminating background noise caused by it sitting in the future. If we simply compared status quo with the ex-ante question, it would be hard to distinguish between changes that occur due to the issue in question and changes that occur due to the passing of time. As an example, ToSIA was used in strategy work of the North Karelia Regional Council in the development of the North Karelian Forest Programme and the Climate and Energy Programme (Lohilahti and Pitkänen 2011). This entailed capturing a vision of a North Karelia free from fossil oil in energy production by 2020 in an ex-ante assessment carried out with ToSIA (den Herder et al. 2012).

If one understands sustainability as an evolving concept (Vucetich and Nelson 2010), one needs to accept that it is inherently based on the individuals’ perceptions of sustainability. The main objective of ToSIA as a decision support system (DSS) is to enable more sustainable activities through the identification of the most sustainable alternative among those analysed, considering the whole value chain, an entire production system, or the life cycle of a product. Most of the time there is no objective best alternative, as oftentimes indicators are pitted against each other – what may be economically sustainable, may not be socially sustainable – the best option strongly depends on subjective perspectives and preferences. A way to integrate individuals’ preferences into the assessment methodology is to connect evaluation methods into the process of SIA. In this sense, ToSIA acts as a platform for SIA.

Case studies have been carried out, for example, to assess trade-offs in competitive land-use alternatives, where reindeer husbandry and commercial forest management coincide (and collide) (Berg et al. 2016) and for contrasting alternatives in land-use planning in Scotland (Pizzirani et al. 2010; Pizzirani 2011; Edwards et al. 2012a). Stakeholder engagement has been actively employed in designing value chain scenarios and the selection of relevant indicators for decision support (Wolfslehner et al. 2012; den Herder et al. 2012; Tuomasjukka et al. 2013a; Haatanen et al. 2014). It has been recognized that an assessment is only as good as the data used to make the assessment (Berg 2011; Weimar et al. 2011), and this is further emphasized in a stakeholder context. If the alternatives to be weighed against each other do not differ adequately, the effect of the user preferences will also be minimal and show no significant preference difference between alternatives.

Integration of ToSIA with several DSSs have been made. The methods presently configured to work with ToSIA are Multi-Criteria Analysis (MCA) using the Promethee approach (Brans et al. 1986), Cost–Benefit Analysis (CBA) (Pearce 1976, 1998) and Policy Analysis (PA) (Vogelpohl and Aggestam 2012). ToSIA’s calculated indicator impacts are offered as a data source for further analysis to MCA, CBA, PA, or any other methodology capable of being adapted to utilize the quantified impacts from ToSIA.

The MCA module provides the possibility for stakeholders (groups or individuals) to give individual preferences to indicators, which helps to compare and interpret pure value-based sustainability impact results expressed in varied units (e.g. money, number of accidents, emissions, or female employment) (Wolfslehner et al. 2011, 2012). MCA incorporates participatory methods into the SIA, which has been considered very useful in DSSs (Menzel et al. 2012).

ToSIA CBA considers both the costs and the benefits of proposed alternatives, and incorporates the environmental and social externalities of the proposed alternatives by giving them monetary valuations (Prokofieva and Thorsen 2011; Prokofieva et al. 2011a). CBA contains the decision-making rule that benefits should outweigh costs, a concise output for decision making.

The design of the coupling of the PA module is mostly conceptual. For the creation of the PA database, 235 policy documents were inventoried for references to the EFORWOOD indicators (Berg 2011; Rametsteiner et al. 2011b). A total of 518 counts of use of these indicators were found (Vogelpohl et al. 2011). The policy database compiles the policy documents, and instances of EFORWOOD indicator use and lists the targets and thresholds specified by the policy documents. To link the policy targets with the ToSIA results, the direction of change advocated by the policy is specified as “maintain”, “increase”, or “decrease” – this enables analysis of whether the directions of change in ToSIA indicator results go towards or away from defined policy targets.

ToSIA can both act as a platform, which can feed different decision support tools with data for analysis. The advantage of linking to different evaluation methods is that they serve slightly different purposes and user needs. While MCA is particularly useful in participatory decision support processes with different stakeholder groups involved (Tuomasjukka et al. 2013a), there are decision makers who prefer monetary evaluations of decision alternatives with CBA. As these methods are used within the same ToSIA framework, the results of different evaluation methods can also be compared. Though highly relevant for the ToSIA methodology as a whole, this thesis does not cover the integrated DSS tools in further depth, as they are not to a significant degree addressed by the papers included in this thesis.

Assessing and calculating multiple and cascading material cycles

The third research question (RQ3) focussed on the issues specific to value chains with several lifecycles, including cascade use and recycling/repurposing. The question of how cyclic value chains can be calculated was already presented with some practical examples for illustration. In these types of value chains, the question of substitution often plays a role. Over the lifetime of raw material, it can be incorporated into several different products. If we do not simply focus on products, we can have a resource perspective: what can be done with a given raw material, such as the forests of a given province? ToSIA can use actual inventory data on local resources. What is the best use of this resource? If harvested and cascaded, a wood-based product can be incorporated in many different products over its lifetime. For

example, paper is first used as high-quality magazine paper, recycled, and then remade into newsprint, which in turn after a few recycling loops can be made into insulation material for houses. When the insulation material reaches its end of life, it can finally be incinerated to substitute fossil fuels. Paper recycling reduces the need for virgin pulp, the organic paper-based insulant substitutes sand-based glass-wool, and finally the incinerated insulant substitutes fossil fuels or, for example, virgin wood chips. There are several ways to see the role of substitution here. If we consider the demand for a product fixed, by using a raw material as many times as possible, we can either reduce the use of non-renewable raw materials or reduce the consumption of virgin renewable materials. Alternatively, cascading can be used to meet the need of an increased demand, thereby avoiding increased consumption of a non-renewable resource or of a virgin renewable resource. Assessing the substitution alternatives in ToSIA, and remembering the points raised in discussing RQ1, this may imply comparison between two fundamentally different raw material value chains. Care must be taken here to achieve balanced assessments. System expansion and use of data on indirect effects should be considered.

It is the author's view that there is intrinsic value in letting non-renewable resources stay undisturbed. Once consumed, many of them can no longer be regenerated, without significant effort. This view is shared in the framing of the Material Input per Service-unit (MIPS) concept for ecological backpacks, which is divided into five categories, one of which is the abiotic material flows (Schmidt-Bleek 1993). Schmidt-Bleek argues that according to the cautionary principle, natural systems should be changed as little as possible and as slowly as possible, as all the extraction of resources cause changes in the ecosphere, and the impacts of these changes cannot be forecasted. While this argument also applies to biotic resources, biotic resources have a regenerative capacity, so favouring a renewable material can at times be justifiable despite it being more energy or economically inefficient to do so (at least without system expansion to cover the effort needed to recreate the consumed material). Questions like these involve trade-offs, and the optimum answer is subjective to, for example, a given time frame or other objectives of such a comparison. However, such questions with trade-offs can be addressed appropriately using, for example, an MCA approach. The next chapter continues this point, by discussing how to allocate sustainability impacts, e.g. between different steps in a cascading value chain.

Allocation of impacts using topologies

The fourth and last research question (RQ4) posed how can one product from a larger value chain be singled out, and allocated a proportion of the calculated indicator results. The allocation algorithm developed for ToSIA (paper IV) is intended for use in large value chains, where we want to be able to see what role a specific product plays in the larger whole. It takes into account all the processes along its life cycle. In LCA-related literature, addressing allocation of impacts from multifunctional processes has also been addressed in the “process flow diagram” approach of LCI (Suh and Huppel 2005). This approach has considerable similarities to the way that ToSIA value chains are set up. In fact, it could be argued that the work that compared ToSIA and LCA (discussed in the section dealing with RQ1; Karvonen et al. 2018) implemented the “process flow diagram” approach, in preparation for the LCA analysis – using ToSIA. ToSIA can also be used as a method to carry out detailed LCIs with the “process flow diagram approach” by offering an established method for the analysis of complex value chain topologies that include loops. Paper III of this thesis deals with cyclic value chains and paper II exemplifies a case study that highlights considerations related to

cascading value chains. Unfortunately, paper IV predated papers II and III, and did not yet consider allocation in cyclic value chains. Though a highly interesting topic, topological allocation in cascading and cyclical value chains was thus not covered in this thesis, and nor has it been addressed in other ToSIA-related publications. Luckily, we can here refer to the body of knowledge from LCA, where different approaches are utilized for allocating the impacts between different lifecycles or cascades. An apt summary of different approaches is presented in Wolf et al. (2013):

“The cut-off method (100/0) considers that environmental impacts of a product should be directly assigned only to the product that causes them. Hence, the primary material burden is assigned to the life cycle burden for the first product (Nicholson et al. 2009). It accounts for the environmental impacts at the time they occur: if a product is made e.g. of primary metal, the environmental impacts of primary metal production are attributed to this product. Avoided burdens – in case the metal in the product is recycled when its service life ends – are not accounted for, discouraging design for good recyclability.

The 50/50 method distributes the burdens of virgin material production and waste treatment to the first and last products in equal proportions (Ekvall 1994), without considering however the specific causes for material loss at design or end-of-life treatment.

In the Substitution method (0/100), the environmental burdens of avoided primary production are credited for the amount of recyclate that is produced at the end-of-life of a product. The use of recycled materials is not considered (Ekvall 1994), hence discouraged.

The ILCD Recyclability substitution method captures the actual, physical consequences of using recycled materials in a product and allows to account for benefits and impacts due to EoL processes (e.g. recycling, landfilling, produced recyclate etc.). This includes the downcycling effects on recyclate quantity and quality (i.e. changes in inherent properties of materials) and also energy recovery (EC-JRC-IES 2010b)”.

From these LCA definitions we can see that all these approaches could also be applied to ToSIA, when needing to assign sustainability impacts to a specific product along a cascading value chain. Likewise, we see that when looking at the issue on a value chain level, the question becomes value chain internal – as the recyclate primarily substitutes virgin material – both of which are likely to be covered by a ToSIA value chain. The substitution takes place inside the value chain, and not outside it. Of course, if something outside the value chain is substituted, it should be then incorporated into the study (system expansion) to make a fair comparison between alternatives.

Future development

There are two main interlinked challenges for improving the scalability and applicability of ToSIA. The first challenge relates to measures to ease the burden of data collection for carrying out case study work. The second challenge relates to improving the scalability and dynamism of the alternatives, currently limited by the static nature of data collection for a narrow case context. There is also potential for more innovative use of ToSIA in more specific research contexts, as outlined below.

Application of ToSIA

The chapter “Applications” described some of the flexibility of application and methodological development carried out in the context of the papers included in this thesis. Beyond those papers, a large body of work has been carried out in applying ToSIA and extending its methodological reach.

An overview of several case studies ranging from regional to EU-wide scale is presented in Lindner et al. (2012). Examples of alternative regional forest management case studies have been presented by Berg et al. first comparing forest management alternatives in Germany and Sweden (Berg et al. 2014) and next comparing forestry and reindeer husbandry taking place in the same forest area in Sweden (Berg et al. 2016). Logging operations at different geographic scales have been assessed using ToSIA (Berg et al. 2012), and the impacts of shifting log transport from road to rail has been evaluated in a regional case study (Fischbach and Becker 2010). Den Herder et al. (2012) show a province-level bioenergy case study in Finland, and Werhahn-Mees et al. (2011a) and Martire et al. (2015) describe the effects of increasing bioenergy production in Nordic countries and Italy, respectively. Paper II of this thesis uses a case of material use vs. renewable energy to demonstrate the use of ToSIA on a cascading (open loop) value chain.

Beyond typical case studies on forest resource based production systems, there have been studies to explore and expand the range of questions that ToSIA can be applied to. The aim has always been to create a method with as few topical restrictions as feasible. In this regard, cases studies on other topics have been of interest for validating the methodological robustness of ToSIA.

Given that ToSIA calculates the material flows throughout value chains, typically for carbon-based materials, it is well suited for modelling the carbon stored in various stages of the value chain’s products, also intermediate products. ToSIA has been used as a tool for assessing changes in carbon stocks in the forests and harvested wood products in Lithuania (Jasinevičius et al. 2017), and its value chain based material flow calculation approach was used in comparing different carbon accounting methods, using a case study in Czech Republic (Jasinevičius et al. 2018). To make ToSIA more suitable as a carbon accounting tool, incorporation of different decay functions besides a simple half-life and adding a time dimension to model changes over time in production of harvested wood products and consequent temporal effects on carbon stocks (Jasinevičius et al. 2015). While these changes are proposed, they have yet to be implemented.

ToSIA allows for a resource-based perspective (Figures 6 and 7), relating the natural resources whose use is being evaluated, to the actual land area producing them. Attaining information on present and especially projected future forest resources is very relevant for analyses. There are many sources for such information. On the national level there are tools such as the forest management planning system MELA (Kilkki et al. 1977; Siitonen 1993), which has been applied for regional case studies with ToSIA (Haatanen et al. 2014; den Herder et al. 2017). The European Forest Information Scenario Model (EFISCEN) produces projections of forest resource development for many European countries in a harmonized manner (Nabuurs et al. 2000; Schelhaas et al. 2007; Verkerk et al. 2016b). This information in spatial availability of forest resources (Verkerk et al. 2011, 2015) can be used to initialize value chains in ToSIA based on actual or projected forest resources (Hengeveld et al. 2016; Verkerk et al. 2016a). The initial idea for the EFISCEN-ToSIA linkage was to make it possible to model, for example, the impacts of climate change on availability of wood for value chains, and assess how this could affect value chains in the forest-based sector. Linking

the value chains to the areas where their resources are produced (Lindner et al. 2012) also allows for metrics of, for example, how much employment a given land area generates considering entire value chains (Korvenranta 2011, 2014) (Figure 14). This opens up interesting possibilities for spatial comparison of value or employment creation by given land areas, and using that as a factor in decision making. The author would consider it interesting to extend the HANPP (Human Appropriation of Natural Primary Production) concept (Vitousek et al. 1986; Haberl et al. 2007) to other sustainability indicators. Deriving an idea from the above experiments (Figure 14), it might be interesting to examine the usefulness of, for example, GVAG HANPP (Gross Value Added Generated from Human Appropriation of Natural Primary Production) as an indicator of land-use value generation intensity. ToSIA is not alone in considering spatial dimensions of sustainability. A broad review of efforts on incorporation of the spatial dimension into different phases of LCA is given by Patouillard et al. (2018), which also observes the possibility of using geographic information systems (GIS) and the spatialization of elementary flows in LCI related to the production processes of agricultural products. In general, the use of ToSIA for analysing spatial sustainability questions could be of interest, and would be an interesting area of study, with due attention to looking at comparable efforts in, for example, MFA and LCA.

Efforts to ease data collection

Laborious data collection is one of the main bottlenecks for carrying out ToSIA case studies. In the author's view, one of the enablers of success for LCA has been the existence of LCI databases such as Ecoinvent (Frischknecht et al. 2005; Wernet et al. 2016), which give average environmental indicator/impact values for specific material/energy inputs. Use of LCI databases makes LCA studies fast to carry out, but comes with issues of accuracy for specific cases. LCA does not preclude the use of more detailed data, if available. Just as it is for ToSIA, the problem of course is that if data is not available, it is often laborious to compile or collect (Karvonen et al. 2018). Herein also lies the reason why social LCA and LCC have not risen to complement most LCA studies and become LCSA studies. Information related to indicators such as employment, work-related accidents, GVA or energy costs vary much more geographically, and are thus not so easy to compile into a database and correlate with a specific input of an LCA study. It also means that they need to be collected more on a case-by-case basis.

ToSIA represents a holistic assessment approach for multiple sustainability dimensions, allowing for the use of statistical data, and not precluding the use of modelled data (Figure 2). ToSIA is designed to be robust enough to accommodate various sources of information. An early design choice made was to avoid mechanistic interlinkage of many domain-specific models (Rosén et al. 2012; Päivinen et al. 2012) that could choke in harmonizing too many conflicting assumptions. While such models could provide for the capacity to dynamically produce indicator values, running many independently developed models in parallel and harmonizing their assumptions to get meaningful results could become overly complex (side note: though this is what OpenMI has been developed for).

Another considered way of creating capacity to provide dynamic responses to time or a scenario of change was to implement response functions to describe gradual changes in indicator values in reaction to a scalable alternative. This approach was also decided against, as a preceding impact assessment project of similar character had experienced trouble implementing their response functions, especially due to the data collection needed to empirically define the response functions. It was estimated that to introduce a scenario for a chain of 100 processes, with approximately 100 different indicators and presuming you need

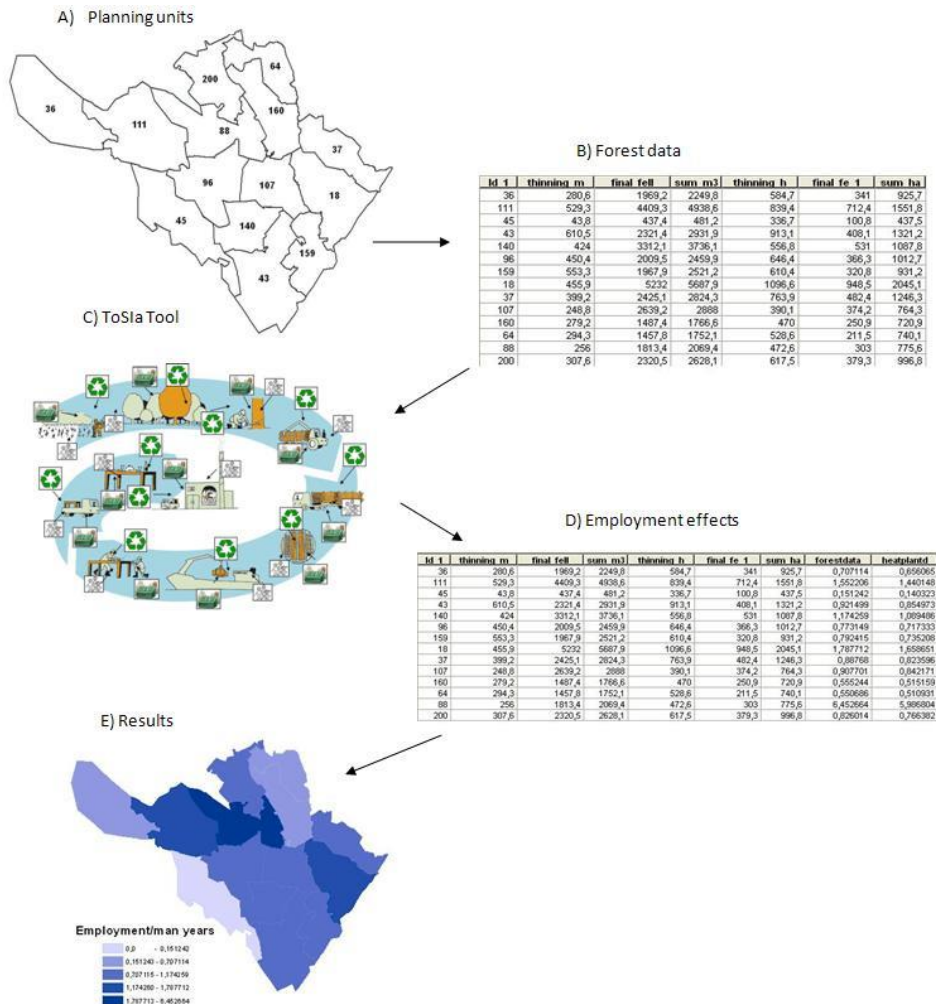


Figure 14. (Korvenranta 2011) shows the phases of connecting ToSia with GIS. In A) the forest planning units are presented as GIS data, B) shows the amount of wood harvested (by harvest type) from each planning unit, which is used to C) initialize flow calculation in ToSia. ToSia indicator results D) are distributed spatially in relation to the wood flows from each planning unit. In case of centralized processing, each process in the value chain is associated with a location. Finally, the results are visualized spatially.

four data points to define the response function, one needs to collect 40 000 unique data points in order to introduce a single scalable scenario into one chain. Considering that at the time we wanted to study several chains with several scenarios and reference futures, such an extensive data collection (over a million data points) was beyond any reasonable means or a rational use of resources.

It remains of great importance for ToSIA to find a way to incorporate more dynamic ways to produce indicator values. An indicator dependency modelling tool that would allow the data collection to be reduced to the identification of values for key drivers could do just that. The rules by which indicator values can be derived from identified key drivers, can be defined as equations – that can be produced analytically rather than as response functions plotted from observed data points. The case and domain-specific exploration of systemic dependencies of indicators on each other has been carried out by Vötter (2009) for forest operations and Chesneau et al. (2012) for transport, along with spreadsheet tools. These typically targeted tools have been directly tailored to produce indicator values for the indicators defined for ToSIA. They are designed to cover specific subsections of forest-based value chains for specific indicators. This work is highly useful for ToSIA and represents the best concrete efforts on this track so far. The question arises, what if a more robust and generic framework could be developed? For example, work has been undertaken to map correlations between the UN SDGs (Lo Bue and Klasen 2013; Pradhan et al. 2017; Neumann et al. 2018). The author has carried out preliminary experiments with the Consideo iMODELLER (Neumann 2013, 2014), which allows even complex indicator correlations to be described exactly with equations as well as in a visually attractive manner. This is one promising avenue of further work and ToSIA development regarding the productivity of its use and usability in general. The endgame of mapping the dependencies of indicators would be the capacity to dynamically create new alternatives, or even use the equation-based dependencies for optimization to attain desired indicator targets or thresholds.

For the author of this thesis, the modelling work presented and discussed here leads to the question of (semantic) interrelationships between modelled entities. Essentially this relates to a modelled value chain as a whole, value chain topologies as networks or graphs of modelled components, or the relationships of the indicators themselves to each other, and the assumptions used to produce these. There needs to be a common language for expressing standardized drivers and parameters, both regarding format and content. It is the author's view that the way to go is using semantic ontologies combined with linked data. This will be discussed next.

Understanding cyclic influences leads to system dynamics

The calculation of cyclic model linkages was achieved through the innovative application of the Open Modelling Interface, the first application of OpenMI in this domain and with this magnitude of models interlinked. The challenge in the adoption of OpenMI was how to deal with cyclic value chain topologies and prevent the software from entering eternal recursion. While a solution to address this problem was created and presented in this thesis, it seems we have not been the only ones faced with this problem. A very similar problem has been identified and a solution has been presented a few years before our work by Suh and Huppel (2005). Paper III demonstrated that it is possible to design a general analytical solution to solve the calculation of looping material flows. Building an automated analytical solution, an autonomous algorithm that creates an analytical solution for all cases is complex, costly, and time demanding to implement. The simulation-based solution using approximation that we

used is adequate for most needs. However, further complexity looms ahead: a model's output might influence its own inputs/parameters, or another linked model's input parameters. This results in cyclic causality, where the equilibrium of cyclic influences must be resolved for correct and harmonized parameterization. A simple example could be that a significant increase in wood consumption in a value chain under study could lead to such an increase in demand and hence the price of wood that the value chain's own assumptions on its own inputs no longer hold, and causes itself to become unviable. A more detailed analysis of this interesting question is beyond this thesis' scope as these questions are currently not explicitly modelled in ToSIA and are left up to the judgement of those defining case studies.

Abstracting from the previous, we move to discuss interlinking models in general. The model linkage framework OpenMI defines information that components can exchange: *what, how much, and when?* OpenMI is not meant to be aware of the internal state of the models encapsulated as *LinkableComponents*. For the sake of coherence and consistency of the *Composition* it might be necessary that many other things are harmonized than just the information that is exchanged. Assumptions and parameters might need to be harmonized between the components, in order for the results to make sense. When the models/*LinkableComponents* operate in the same conceptual space – they may not genuinely be decoupled from each other. In the case of ToSIA, two processes modelling a form of transport in different parts of the value chain, should probably use similar energy prices, and projections on their future development – use harmonized assumptions. There are two main ways that these assumptions can be harmonized: (1) either the harmonization is done externally by the human actor responsible for performing the modelling (ensuring inputs to two decoupled models are harmonized); or (2) the modelling is extended onto these parameters – a form of system expansion. This means that the models themselves need to be able to “ask” for their parameters, and all parameters themselves will need to be encapsulated as models of their own (though the model can simply be one value). Models should also have a way to express when these parameters are beyond their applicability or perhaps as a degree of elevated uncertainty. It is the author's understanding that conflicting assumptions between models are a common source of errors, discrepancies, and uncertainty in modelling work. Ensuring that all the models in a complicated *composition* receive parameters that are within the boundaries of applicability for the model, becomes something to be managed. All of this results in an intricate web of modelled components, with numerous types of exchanged information. Not to mention that each *composition* can also be a *LinkableComponent* on its own, with specified connection points.

The general systems theory (Bertalanffy 1950) describes complex systems and how the parts of such systems are interlinked. The consequent system dynamics field of research deals with the description and management of such complex interlinkages, discussed, for example, by Little et al. (2019). From a practical point of view, system dynamics tools such as the Consideo iMODELLER² could be ways to handle these networks of causal complexity, but it does not provide the kind of model linkage framework as does OpenMI – what we need is a combination these two. Adding onto this still, according to Kumazawa et al. (2009), “ontology engineering can also help to combine models constructed separately” – a view which the author of this thesis wholeheartedly shares. Ontologies combined with linked data are the missing link here – a language for harmonization in expressing *what, how much and when* is exchanged between models.

² <https://www.consideo.com/imodeler24.html>

Uptake

A lesson learned from this development endeavour is that it is not enough to just create a software solution to a science or policy problem. For the developed solution to have an impact on the state of the art requires persistent financial resources, and a constant effort in both teaching interested users on how to apply the method as well as attracting the attention of potential new users. Research projects have a tendency to fund the development of solutions, but resources to maintain a developed solution are much more difficult to come by. It would require a higher than the current level of uptake to make ToSIA a self-sustaining activity. Uptake does not happen on its own. The modus operandi of propagating ToSIA has been the formation of a ToSIA Management and User Group (TMUG), which is not an association nor any other type of legal body. The European Forest Institute has chaired TMUG and has been actively promoting the use of ToSIA through application in research projects. TMUG has collected small membership fees for keeping the server infrastructure for databases running. A complex software needs constant maintenance, which is costly, and difficult to resource in research projects. Small updates can be managed, but when major migrations between solution building blocks need to be made, this can be a substantial amount of work. It remains an open question how developed scientific software/methods should best be maintained and developed. Some try the community approach by setting up associations. Others form small companies around the knowhow of the method and try to sell its application as a commercial service.

Conclusions

ToSIA is the first software implementation of a method that combines material flow based value chain analysis with indicators of different sustainability dimensions and harmonized system boundaries. From an impact assessment point of view, ToSIA has achieved the goals that it set out to achieve, demonstrated through its application in numerous case studies conducted by various organizations and scholars (see chapter “Applications”). A value chain topology based allocation method capable of using various allocation criteria was presented. ToSIA is a robust method filling a contemporary call for tools to address a policy need. It can be used to: (a) produce information for informed decision making; and (b) as a facilitation tool with its MCA component to stimulate discussion on the relative importance of sustainability indicators for different stakeholder groups. ToSIA is more suitable to be used for comparisons between alternatives in a production system, rather than assessing the absolute sustainability of a given production system.

From a software development perspective, the implementation was innovative in its use of the OpenMI modelling framework. The capacity to handle a broad range of types and domains of value chains increases the utility of ToSIA. However, ToSIA uptake has so far been less than what is needed to generate the financial resources needed for its maintenance and continued development. It is a software heavy set of tools and some resources are needed to keep ToSIA viable and the software and servers running. As has been pointed out earlier, also LCSA is struggling to broaden its user base and increase the volume of application. A way forward for both methods would be to, for example, leverage system dynamics and use networks of interlinked drivers to be able to model also social and economic indicators, along with potential indirect consequences. This would enable different sustainability dimensions to be captured in a more balanced manner, with system expansion capacities. Utilization of a

system dynamics approach has been demonstrated by Neumann et al. (2018), for mapping the interconnections and trade-offs between the SDGs. Additionally, the realized development potential stemming from the integration of the IT concepts of semantic ontologies and linked data together with reformation of the OpenMI could open a new field of open, networked, linked data –based, modelling. The risk is that despite policy calls for solutions, without efforts to both bolster the user community and invest in further development, ToSIA may gradually fall out of use. “Pulling the plug” on the ToSIA servers would effectively end the possibility of carrying out new case studies.

ToSIA is a useful wrench in the sustainability assessment toolbox. It can be used to reach a more sustainable future as it allows assessment of the concrete and quantitative impacts of proposed changes so that we do not fly blind into the dark of decision making. Degrowth (Asara et al. 2015) or other sufficiency oriented economic models and paradigm shifts are needed if we are serious about creating the genuine change needed to combat climate change and reach the UN SDGs. According to Hickel (2019), it is possible to achieve a good life for all within planetary boundaries. It just requires that “rich nations dramatically reduce their biophysical footprints by 40–50%” in order to make room within the planetary boundaries for the increased biophysical pressure needed for poor countries to reach a good life. While another new assessment method will not make changes happen on its own, it is a valid tool for balancing the economic, environmental, and social consequences of the difficult decisions ahead that need to be made.

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APPENDIX A

Development of the formula to calculate flow for vertex of the loop

Let us number the vertices of given loop from 1 to n . If we define:

I_i - external input to the vertex i ($i = 1, n$);

p_i - weight assigned to the edge (belonging to the loop) coming to the vertex i ($i = 1, n$);

$W_{i,j}$ - path (way) from vertex i to vertex j : consequence of edges connected the vertices

$P_{i,j} = \prod_{p \in W_{i,j}} p$ - weight of path $W_{i,j}$ and

$P = \prod_{p \in W} p$ - weight of whole loop path W ;

X_i - flow in the vertex i ($i = 1, n$);

Then

$$X_i = p_i \times X_{i-1} + I_i \quad \text{for } i = 2, n \text{ and } X_1 = p_1 \times X_n \quad (\text{A.1})$$

Let us look at the vertex n :

$$X_n = p_n \times X_{n-1} + I_n$$

As $X_{n-1} = p_{n-1} \times X_{n-2} + I_{n-1}$ then:

$$X_n = p_n \times p_{n-1} \times X_{n-2} + p_n \times I_{n-1} + I_n$$

Continue iterations and taking into account (1.1) we have:

$$X_n = \sum_{i=1}^n P_{j,n} \times I_i + P \times X_n$$

And finally:

$$X_n = \frac{\sum_{i=1}^n P_{i,n} \times I_i}{1-P} \quad (\text{A.2})$$

Input/output flows for a loop

Now we will use the formula (1) to prove the statement that total out ("sink") from the loop is equal to the total input flow to the loop.

For a given vertex the sink is:

$$S_i = (1 - p_{i+1}) \times X_i, \text{ where } S_i \text{ is the sink from vertex } i. \text{ Note that } p_{n+1} = p_1;$$

The total sink is:

$$S = \sum_{i=1}^n S_i = \sum_{i=1}^n (1 - p_{i+1}) \times X_i = \frac{1}{1-P} \times \sum_{i=1}^n [(1 - p_{i+1}) \times \sum_{j=1}^n P_{j,i} \times I_j] \quad (\text{A.3})$$

Or

$$S = \frac{1}{1-P} \times [\sum_{i=1}^n \sum_{j=1}^n P_{j,i} \times I_j - \sum_{i=1}^n p_{i+1} \times \sum_{j=1}^n P_{j,i} \times I_j] \quad (\text{A.4})$$

Taking into account that $p_{i+1} \times P_{ji} = P_{i,i+1}$ and loop topology - we can see that there are (in square brackets) $n \times (n - 1)$ pairs of summands $P_{k,m} \times I_l$ with opposite signs, which gives zero in sum.

The only summands I_j and $P \times I_j$ are left in the sum.

Finally:

$$S = \frac{1}{1-P} \times [\sum_{i=1}^n I_i - \sum_{i=1}^n P \times I_i] = \frac{(1-P) \times \sum_{i=1}^n I_i}{1-P} = \sum_{i=1}^n I_i$$

Q.E.D.