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Summary

Over the past few decades, there has been a transition from a linear "take-make-dump" economy to a circular economy in which materials are reused and recycled at their end-of-life. While modelling and case study analysis are helpful tools to support such a transition (Raven, 2007), quantitative models rarely have been used (Seuring, 2013; Dekker et al., 2012). By means of several case studies, this thesis intends to demonstrate the potential of using quantitative models to support a shift towards more sustainable supply chains. In particular, this thesis aims to contribute to the development of decision-support tools for national policymakers and industrial decision makers in their journeys toward establishing sustainable waste-management policies and sustainable supply chains. In this thesis we use system dynamics and Multi Criteria Analysis to model sustainable waste-management problems.

System dynamics can very well support the development of sustainable government policies (Boulanger and Bréchet, 2005). It is a powerful modelling technique that is used to explain and predict behaviour of real-life supply chains (Towill, 1996) by describing system building blocks and the relationships between them (Sterman, 2000). Moreover, system dynamics is considered to be suitable for modelling the interaction between the earth's systems and human systems (Meadows et al. 1972). However, there have been only a limited number of applications of system dynamics for modelling sustainable manufacturing (Kibira et al, 2009) and sustainable waste management (Morrissey and Brown, 2004).

Industrial decision makers are required to comply with (supra) national and regional legislation on sustainable development. Because of the challenges related to managing the complex trade-offs between economic, environmental, and societal factors, governmental regulations and legislation play an important role in spurring sustainable business activities (Tang and Zhou, 2012). We define sustainability in business processes as the combined economic, environmental, and societal optimum of alternatives that take into account constraints, such as technological limits or legislation. This is also known as the triple bottom line (TBL) approach to People-Planet-Profit optimization (Kleindorfer et al., 2005). Industrial decision makers face strategic and tactical questions as they consider a range of options and seek to make the most sustainable choices at various points in their supply chain—from product development to manufacturing to transportation. In general, these questions can be summarized as meeting different objectives, which might be conflicting, subjected to a finite number of constraints. Multiple objective programming is capable of dealing with these types of questions (Munda, 2005). An extensive literature review of Seuring (2013), however, shows that, in the limited number of papers that apply quantitative decision support models, typically only the economic and environmental dimension is present. The societal dimension is seldom taken into consideration (Seuring, 2013; Sharma et al. 2013).

This thesis aims to contribute to the current gap in the literature by presenting system dynamics models used to assess and support national sustainable waste-management policies and by developing multiple-criteria decision models that take the triple bottom line into account for supporting sustainable industrial waste management decision making.

After the introduction in Chapter 1, two system dynamics models are presented to evaluate, in Chapter 2, the municipal solid waste management policy for Flanders, the northern region of Belgium and, in Chapter 3, the end-of-life vehicles waste management policy performance for passenger cars of Belgium. Both models are used to understand the longer-term influence of the main endogenous and exogenous variables that influence the waste management policies under study.

In Chapters 2 and 3 we demonstrate how system dynamics can be used to examine national waste-management policies. Suggestions for improvement will be made using sensitivity analysis. With regard to household waste, we will examine the importance of a prevention policy for keeping waste volume per capita decoupled from economic growth. In Chapter 3 we will present a generic model to examine if and how countries can achieve the challenging 2015 EU recovery and reuse targets on end-of-life vehicle waste using Belgium as a case study. Results show that Belgium is capable of meeting these targets from 2015 onwards if a stable growth in ELV waste is generated to trigger investments for raising the recovery rate of plastics. Such stable growth in ELV waste can be realised by e.g. limiting the export of discarded passenger cars or by decreasing their life span. Moreover we will demonstrate that the quicker authorised treatment facilities react by installing additional recovery equipment for plastics, the sooner the ELV 2015 targets for passenger cars will be met. The models developed are generic and may be adjusted easily to evaluate similar waste management problems in other European Union member states. The novelty of the proposed solution approach is that it takes the dynamic interactions between GDP, population growth, consumer behaviour, legislation and many other specific parameters into account to model sustainable waste management processes. Compared to earlier developed static decision-support and macro-economic models, the proposed system dynamics models allow integrated decision-making time effects and non-linearities to be taken into account.

Next, we study two problems related to the sustainable recovery of green waste. In Chapter 4 we will examine whether composting and/or incineration with energy recuperation is the most sustainable approach to green waste valorisation. Traditionally life cycle assessment (LCA) is not capable of comparing the environmental impact of two valorisation alternatives when the resulting products perform different functions. Therefore, we present an alternative environmental impact analysis method. This method is applied to a case study to assess the environmental impact of different green-waste valorisation options. The proposed method is based on the determination of the Pareto optimal front, representing optimal trade-off combinations of composting and energy recovery of green waste. For determining the Pareto optimal front, the multi-objective programming problem of maximizing composting yield and waste to energy is solved using the *elitist non-dominated sorting genetic algorithm* version II (NSGA-II) (Deb, 2009) and the *ε-constraint method* (Mavrotas, 2007). The methodology is tested on a case from Flanders, the northern part of Belgium. Computational results on publically available Belgian data show how the optimal valorisation of a batch of green waste is determined by its composition of fresh cuttings from pruning and leaves ('brown mass') and grass ('green mass'). The full allocation of green waste, to either energy valorisation or to composting, gives optimal results only if no green mass is incinerated with energy recuperation.

In chapter 5 the green-waste valorisation problem will be studied from another perspective by analysing whether, compared to only composting, it is more sustainable to remove cuttings from green waste to be used for energy valorisation. This question has been challenging to policymakers since they may divert from composting green waste only if it can be proved that an alternative recovery process is more sustainable following the EU waste directive 2008/98/EC (EP&C, 2008). We are the first to present a model that selects the most sustainable valorisation by optimizing profit, environmental and societal impact using the ε-constraint solution approach. Using real-life data we will examine different green waste valorisation alternatives and the impact of subsidies. Computational results will show that, in place of full composting, it is more sustainable to separate a fraction of woodcuttings and sieve overflow, to be used for energy recovery, and to compost only the remainder of green waste. We also will demonstrate how subsidies can change the optimal sustainable recovery solution.

Finally in chapter 6 we will deal with selecting the most sustainable transportation mode for household waste. The options taken into consideration are truck, barge or combined truck-barge transport. By expressing the three sustainability pillars People-Planet-Profit in terms of internal and external costs, a traditional single-objective programming approach can be used. The novelty of the paper is that it presents a dynamic tactical planning model that minimizes the sum of transportation costs, external environmental and societal costs. The presented Municipal Solid Waste Service Network Design Problem allocates waste volumes to transport modes and determines transportation frequencies over a planning horizon. For the case under consideration, we will show that it is economically viable to ship municipal solid waste using multi-modal truck/barge transport for distances below 100 km, a distance traditionally considered to be the minimum distance for such a modal shift (Pekin, 2010).

We conclude in chapter 7 with the main findings of this thesis and we present directions for further research.