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Establishing effective markets for secondary building materials

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Summary

This project was commissioned by the Danish Environmental Protection Agency to support the work of the Partnership on sustainable construction and waste prevention, set up to support the implementation of Denmark Without Waste II. The overall objective of the project is to frame the development towards an effective market for secondary products obtained through reuse and recycling in a large scale. The focus is on the conditions and requirements necessary for establishing an effective market for secondary products that can also help introduce new, innovative business models related to the processing and recycling of construction and demolition waste.

The Partnership has selected three materials, namely concrete, wood and roof tiles wastes for detailed analysis as they are considered to have a higher potential for recycling and re-use as well as for developing new secondary products from them.

For each material, the current market conditions and functioning is investigated, and the barriers that hinder further market development are analysed. Finally, an idea catalogue with proposals that could promote a more effective, flexible and open to innovation market was developed. The analysis is supported by an extensive desktop research, interviews with relevant stakeholders and a mapping of markets and initiatives in other European countries.

The results of the analysis leads to an identification of barriers for further improvement of the market for reused or recycled materials and which stakeholders are involved in the process. The most important barriers seem to be the following: current market inertia, the lack of documentation and guarantees, insecurity of supply as wells as costs associated with waste processing and – in some cases - the presence of hazardous substances in the waste.

Experience from abroad shows that no other EU country has been successful in developing an effective market related to construction and demolition waste management. Small scale initiatives exist that manage, at best, to create niche markets for specific waste applications. Therefore, there is no successful model that Denmark could copy or learn from.

In order to overcome the identified barriers and establish a truly effective waste market, initiatives have been identified together with the members of the Partnership: match-making platforms that help match supply and demand, compilation of standards and documentation, demonstration projects focusing on costs and a more strategic use of green public procurement are considered the most effective tools.

These results are supported by the development of a dedicated economic model. The model simulations of the different initiatives show how market parameters such as price and security of supply are affected. The model also considers the “willingness to consider alternatives to virgin materials”, a parameter that has a decisive influence on market development. The modelling concludes that significant improvements are achievable if key stakeholders work together in a concerted action. However, the expected positive results will occur only in the long run.

Sammenfatning

Nærværende projekt er gennemført for Miljøstyrelsen i regi af *Partnerskab om bæredygtigt byggeri og affaldsforebyggelse*, etableret som et led i implementeringen af regeringens strategi, Danmark uden Affald II. Det overordnede formål med projektet er at fremme udviklingen af et effektivt marked for byggematerialer som sekundære råstoffer til henholdsvis genbrug og genanvendelse i stor skala. Fokus har været på, hvilke betingelser og krav der skal være til stede for at der kan udvikles et effektivt marked for sekundære produkter, der også kan bane vejen for nye, innovative forretningsmodeller i relation til oparbejdning og genanvendelse af bygge- & anlægsaffald.

Partnerskabet har udvalgt beton, træ og tagsten som de fraktioner, der skal belyses, idet det antages at disse materialestrømme har det største potentiale for at blive udviklet til nye, sekundære produkter.

For hvert materiale undersøges de nuværende markedsforhold og dets funktion; barrierer for videreudvikling af markedet samt et idékatalog med forslag, der kan fremme et mere effektivt, fleksibelt og innovationsåbent marked. Analyserne er understøttet af et omfattende litteraturstudie, interviews med interessenter samt kortlægning af markeder og initiativer i andre europæiske lande.

Resultatet leder frem til identificering af barrierer for videreudvikling af et marked for genbrugs- og genanvendelsesmaterialer, samt hvilke aktører der skal involveres i processen. De vigtigste barrierer synes at være den nuværende inerti i markedet blandt vigtige aktører, manglende dokumentation for produktets egenskaber, uklarhed om garantier og usikkerhed omkring en stabil forsyning, omkostninger ved affaldsbehandling samt i visse tilfælde tilstedeværelse af farlige stoffer i materialerne.

Undersøgelsen af forhold i andre lande viser at ingen EU lande har opnået effektive markeder for genbrug og genanvendelse af byggematerialer. Der findes enkelte succeshistorier, men kun i lille skala og for specifikke materialer. Der er således ikke en succesfuld model eller metode, som Danmark kan kopiere eller lære af.

I samarbejde med Partnerskabets deltagere er der udviklet et katalog over de virkemidler, som anses for de mest effektive initiativer og som bør tages i anvendelse for at overkomme eller reducere barrierene: Matchmaking platforme så udbydere og efterspørgere kan finde hinanden, udarbejdelse af standarder og dokumentation, demonstrationsprojekter med fokus på omkostninger samt en målrettet strategi for anvendelse af grønne offentlige indkøb ved byggeri og renovation.

Ovennævnte resultater understøttes af en model, der blevet udviklet som et led i projektet. Simuleringer af forskellige initiativer viser – under visse antagelser – hvorledes forskellige parametre (f.eks. pris og forsyningssikkerhed) påvirkes. Modellen opererer også med et begreb, der har afgørende indflydelse på disse markeder, nemlig ’villighed til at overveje alternativer til nye (virgine) materialer´. Modelberegningerne viser, at væsentlige forbedringer frem mod et effektivt marked kan opnås ved en større, målrettet indsats, men at det forventede positive resultat først kommer på lang sigt.

1. Scope

1.1 Policy background

The European Union and the national Danish legislation have been focusing on improving the waste management for construction and demolition waste (C&DW) for around a decade now. Denmark has traditionally been a frontrunner in the EU in terms of C&DW recycling with high recycling levels already from the 90s. Moreover, Denmark has achieved recycling levels higher than the EU 2020 relevant targets, therefore the country has been so far little affected by EU policy developments.

In light, however, of the forthcoming circular economy package, the retained focus on C&DW is taking a different shape. Other life cycle phases of a building, such as construction and use are starting to be considered as crucial for delivering improvements in waste management and contributing to the establishment of a circular economy. The Danish Advisory Board for Circular Economy has included numerous recommendations to the Danish government that affect C&DW management.

Under this context, new business models arise also in the field of C&DW. New markets might emerge that are called to accommodate new, innovative products based on waste materials. Therefore, new questions arise such as: “How can an effective market be established that leaves room for innovation and serves the purposes of a new, more circular world?”.

This project attempts to answer this question in a Danish context, by focusing on the material markets of three distinct C&DW materials: concrete, wood and roof tiles.

The project has been commissioned by the partnership on sustainable construction and waste prevention, established in 2016 as a result of the new waste strategy, Denmark without waste II. The aim of the partnership is to increase the resource efficiency in the sector, to manage the safe disposal hazardous substances and to diffuse knowledge around sustainability in the construction sector. The partnership functions as a reference group for this project.

1.2 Project objectives

The high-quality management of construction and demolition waste (C&DW) has a long history in Denmark. C&DW management has for a few decades now, focused on the sound and safe handling of waste and on increasing recycling or at least energy recovery. Denmark has, for example, fulfilled the EU recycling targets for C&DW (2020) already since the beginning of 1990s. Recycling, in terms of quantity, has not been the focus of improvement for C&DW management; instead the quality of recycling can be improved.

The bulk of C&DW is composed of materials that can be developed into secondary raw materials with relatively low economic value (apart from metals), such as aggregates. Its recycling leads to products that normally cannot fetch high prices, while at the same time the recycling processing and transportation costs[1] are comparatively high. These framework conditions mean that only few recycling applications can have a guaranteed viability in a market context, rendering the C&DW market in Denmark rather inflexible.

On the other hand, a continuous improvement, in terms of environmental savings and creation of economic value, in the recycling and re-use market is a stated objective of the building industry. In fulfilling these objectives, new ideas for waste management and the development of new secondary products are vital elements. Thus, there is a need for the Danish C&DW market to become more flexible in accepting innovation and in promoting higher quality waste management options (e.g. re-use) through market mechanisms.

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[1] Transportation costs for heavy and voluminous material such as C&DW can be decisive for estimating the overall cost of recycling.

The main objective of this project is to analyse how the existing secondary material markets in Denmark can become more effective in contributing to innovation, delivering higher quality secondary products and in securing more environmental benefits through C&DW management. In other words, this project sets to investigate how the markets can shift focus towards supporting a more circular economy.

We set out to investigate what are the requirements and necessary conditions for an effective market to be developed around secondary construction materials and what is the corresponding time frame. We look into the current situation separately for each material with the view of understanding how re-use and high quality recycling activities can become competitive with respect to alternatives based on virgin materials. We employ economic theory and a corresponding economic model, developed specifically for this project, in order to simulate the requirements and conditions for establishing an effective market.

The focus of this project is recycling and re-use of C&DW. Re-use refers to business activities where products or components, that have not yet become waste, are used again for the same purpose for which they were manufactured. Preparation for re-use refers to recovery operations in the form of control, cleaning or repair on products or components, that have become waste and with the aim at improving them so that they can be re-used without further processing. In this report, we use the term "re-use" for both these definitions. With the term recycling, we refer to the traditional waste processing for material recovery of waste materials with the aim of producing new, secondary materials that can enter the economy again.

1.3 Project scope and planning

The main objective of this project, i.e. how to establish effective markets for C&DW, is further detailed into the investigation of the material markets for products from three waste materials: concrete, wood and roof tiles. Note that the focus is on new products or treatment options entering the market that have the potential for large-scale market changes. That means that new products that aim at creating niche markets of a limited influence on the overall waste market are not relevant for this project.

The analysis of these three waste material markets takes existing knowledge as a starting point in order to frame the current market conditions and to describe the existing recycling and re-use routes for the three materials. Through this desk study, some barriers are identified that prevent the existing markets from further development. These barriers may be of regulatory, economic or technical nature.

Further, case studies (both successful and unsuccessful) from Denmark and abroad are used for completing the analysis. The case studies offer useful insight in the market properties that hinder or promote the establishment of an effective market for waste materials.

A third pillar of the analysis is the completion of five interviews with stakeholders across the waste market value chain. Interviewees are selected so that they are both representatives of different parts of the value chain but also according to their expertise with respect to the selected materials. The interviews also contribute to a better understanding of the existing and a potential, effective market and reveal stakeholder-specific barriers for market development.

These three pillars of the analysis result in the compilation and detailed description of regulatory, economic and technical barriers that affect the existing markets and prevent them from being able to accommodate new innovative products effectively. The barriers are presented separately for each material examined, as well as generic barriers that apply to all materials.

The identified barriers will be scrutinised in order to come up with proposals on how to overcome them. These proposals are in the form of interventions to the market functioning that change the current market conditions in order to increase the market effectiveness in promoting new innovative products that are based on high quality recycling and re-use. The proposals are analysed in terms of expected impact they have on the market and are grouped together so that they form an idea catalogue that can be fully or partially implemented in the future.

The analysis of barriers and opportunities (idea catalogue) takes into account the supply and demand perspectives. The supply perspective can add important parameters to the analysis of barriers and opportunities by précising the market size and potential. On the other hand, the demand side affects the barriers discussion as the demand for materials sets various technical and quality requirements on them.

In order to understand better the effect that the implementation of improvement initiatives might have on the building materials' markets, a modelling exercise is performed. First the flows of materials in the three material markets is simulated. The flows are regulated by specific properties of materials (either virgin or recycled): Price, quality and willingness to consider. These properties that determine the market share of each product, are influenced by the improvement initiatives.

The following chapters describe and structure the analysis along the lines of the aforementioned three pillars, namely desk research, case studies and interviews. A list of barriers is presented and a corresponding idea catalogue for overcoming them is described and assessed. The assessment of the catalogue is done through an economic systems analysis approach where a modelling of future developments based on the implementation of the idea catalogue is attempted.

2. Secondary building materials markets in Denmark

The existing or potential markets for the three waste fractions treated in this report share certain characteristics that pose specific challenges for their development and future operation. Many of these characteristics stem from general features of waste markets, particularly when comparing them to the corresponding virgin materials' markets. In the following, we outline general characteristics of secondary materials markets, particularly as they apply to the construction industry, and then focus on the specific features of the three waste fractions, concrete, wood and roof tiles. Where applicable, we further point out features that are specific to Denmark versus those that apply to the EU market in general.

2.1 Generic characteristics of secondary materials markets

2.1.1 Functioning of an ideal market

From an economic perspective, an ideal market would function so as to allocate the different waste materials to uses that would maximize the benefit to the buyer relative to the cost to the supplier of providing the materials and the societal costs incurred in the process. While this concept is simple in principle, it is more difficult to assess the requisite costs and benefits in practice. In the context of waste markets or secondary materials, a key element is the extent to which re-use or recycling can be done at "higher" quality levels of the circular flows. For instance, the re-use of a concrete pre-fab element would represent a higher-quality flow than crushed concrete used as aggregate for new concrete production, which in turn represents a higher quality application than crushed concrete used as filling or for firming material in roads. A proper assessment of the functioning of the market would amount to summing up the full social cost and benefits involved, compared to the alternative uses or disposals of the waste products. Naturally, this is an extensive exercise, beyond the scope of this study. Here, the focus is primarily on the characteristics of the waste market and the typical barriers they imply for a smooth functioning of the market.

2.1.2 Waste as a "high-entropy" product

Perhaps the most obvious feature of secondary materials is reflected in the word "waste" used to characterize their current status in the productive system. Traditionally, waste products from construction, whether they are generated in the construction process or from the demolition, are considered to have very little inherent value, apart from the potential heat that can be released through incineration. To the extent that the waste is a mixture of different fractions (wood, soil, concrete, tiles, glass etc.), it also represents a "high-entropy" product of low quality, which it would take time and energy to sort into higher-value fragments. While much can be achieved through careful organization of the demolition and construction, and even more can be achieved in the long run with buildings designed for disassembly, the process will inherently involve effort and/or time.

2.1.3 Quality and consistency

Unlike a normal product market, where the material inputs and the manufacturing process can be tightly controlled so as to deliver a **standardised product of consistent quality**, secondary material markets arise from a dismantling or destruction of different original products where the conditions will differ from project to project. In the case of the construction industry, the original structures vary greatly with respect to age, construction method, material, etc. Therefore, it is difficult to assure a uniform quality of the material. This applies both the technical properties (strength, color, purity, dimensions, etc.) and to the possible presence of problematic substances.

Furthermore, since waste arises as a by-product of a primary process with a different purpose, it is dependent on when and how this primary process occurs and **cannot be manufactured "on demand"** in the same way a virgin product can. In the case of construction waste, the primary process is the demolition of existing structures and the waste generated during the construction of new structures. Initiation of construction is driven by developer decisions on new projects and not by the desire to produce more secondary material. Therefore, secondary materials streams are inherently less reliable and consistent than virgin materials. Sometimes they may not be available in the quantities needed, or the delivery delays may be prohibitive. This becomes even more of a problem when one considers the importance of timing in construction projects.

It is possible, of course, to improve the consistency of the materials through selective demolition, more extensive sorting and post-demolition treatment (cleaning, etc.), and quality test and certification. Likewise, one could achieve more constant output levels and hence reliability of delivery through large-scale stockpiling. However, these additional steps inevitably impose costs on the market, particularly when they are not well established and done to scale. In the case of the construction industry, the stockpiling cost would be particularly large as materials are **bulky and heavy**.

Another way to increase the re-use or recycling of material is to include it directly on-site in the construction process. To the extent that this is possible, this immediate and direct re-use or recycling represents the highest economic and environmental value. Such direct use is possible, besides new buildings, in renovation or refurbishing projects, e.g. by re-using roof tiles when repairing or remodeling the roof of an existing building.

2.1.4 Misalignment of ownership and capabilities

One issue common to all waste markets relates to the ownership of the waste. Traditionally, the waste ownership has resided with the organization charged with responsibility for disposing of it. During a building demolition, this would initially be the contractor responsible for the demolition. As the contractor hands over the materials to the waste management organization, the latter assumes responsibility for the treatment. Treatment can mainly take the form of recycling or re-use, incineration in local heating plants, or deposits in landfills. The two latter cases are typically handled by municipalities.

In the minds of the typical waste management agent, whether a demolition firm, a trucking company responsible for disposal, or a municipality, construction waste has traditionally been thought of as a low-value material that can at best be used for low-level recycling in the form of firming or filling material (e.g., crushed concrete or tiles) or incineration (wood). These agents may not always possess all the requisite knowledge and capabilities to upgrade the waste by separating it into purer fragments of consistent quality (though they could no doubt develop these over time), nor do they have the capabilities for marketing them to potential buyers, such as assessing the market potential, risks (including possible liability issues), and pricing of materials. Given this barrier, current owners are unlikely to perceive much value in developing recycling or re-use markets.

In order for a market to function effectively, an intermediary is needed that would receive waste material from demolitions and/or construction processes, process it into standardised, certified product categories, and market and distribute the products to potential buyers, whether they be construction contractors, developers, or engineering/design/architecture firms. This intermediary role could be assumed by existing actors in the industry, such as the demolition contractor, a trucking firm, the construction contractor, or a specialised third-party firm. In the case of waste generated during the construction process, the role could also be assumed by the materials supplier by take-back schemes or, more radically, by taking over the on-site materials logistics. But regardless of who will eventually step into this role, it will require time to evolve the organizational setup and operational and marketing experience.

2.1.5 Market learning

Since markets for high-quality re-use and recycling of building materials waste are currently largely non-existent, developing them will involve experimentation and learning by doing. Studies of innovation have shown again and again that radical innovations, where both the way the products is produced and the way it is used by customers are different from the past, are notoriously difficult to predict. When the product is unfamiliar to customers, they will have a difficult time telling you what it is worth to them (their willingness to pay) or how much they would be using it (demand). Customers will only discover this over time as they start adopting the product or talk to other market participants who have experience with it. Likewise, on the producer side, the cost of processing, distribution, certification and marketing is highly uncertain and likely to change dramatically over time, as more efficient systems are developed and as managers and employees gain experience with the workflows and routines involved.

The presence of such learning curve effects represents a barrier for potential entrants to the market: Costs are likely to be high on both the supplier and customer side of the market, which limits the initial demand needed to drive the development of the market. Moreover, customers' perception of quality and reliability is likely to be low, until a consistent track record has been established. Thus, while a thriving recycle and re-use market may be possible in the long term, it may never develop due to the insurmountable cost obstacles before learning has taken place.

On the other hand, to the extent that learning curve effects benefit individual producers and cannot easily be imitated, they can represent a first-mover advantage for suppliers: By building up the expertise and the market system early, suppliers may gain a cost advantage that is difficult for new entrants to beat, thus giving them some degree of market power that can form the basis for attractive economic rents (profits). If such a learning-curve advantage is large enough to bestow monopoly power to the supplier, it may then be necessary to introduce some degree of regulation to assure a socially optimal functioning of the market.

2.1.6 Scale and scope economies

One feature of the logistics and processing structures surrounding waste collection and handling is that there appears to be widespread economies of scale and scope. The larger the volume of the recycling and re-use business, the more individual variations in the types and quantities of materials can be averaged out, and the wider the selection of possible categories of some materials (like roof tiles) will be available at any time. Moreover, the operation of the logistics system (trucks, containers, storage sites, sorting facilities, demolition equipment, etc.) is likely to exhibit economies to scale.

2.1.7 Geography and natural monopolies

Given the bulky and heavy nature of building waste materials, compared to the relatively low value of the product, transportation costs and hence geographic location are likely to play a significant role[2]. This implies that the markets are likely to be geographically defined, with most competition being local in nature. When coupled with potential scale and scope economies, it may therefore be the case that waste handling constitutes a natural monopoly, i.e., a situation where the most efficient (lowest cost) provision of the material would be provided by a single or a few suppliers. If this is indeed the case, it implies that a socially optimal functioning of the market would involve some form of regulation, either in the form of a publicly owned supplier of waste materials or in the form of monopoly regulation[3].

2.1.8 Timing and management attention

As mentioned, the construction industry is extremely time-sensitive: Given the high capital costs involved in most construction projects and the substantial coordination costs associated with delays in any part of the construction process, time overruns are expensive and constantly a prime focus of management attention. This implies that any activity that is time consuming and on the critical path in a construction project will inevitably be subject to cutbacks. More subtly, it also implies that managers' mental models of the business will inherently view such activities with a great deal of suspicion.

In order for a market for secondary materials to be successful, these time pressures must be considered. Some of the solution may be in moving activities off the critical path, through early planning of demolition and construction and mapping of resources, for instance. Part of the solution may also be in the above-mentioned learning-curve effects: Much of the costs involved in waste materials processing are directly time related and learning-curve effects are likely to manifest to a great extent in shorter processing times.

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[2] It is estimated that a 20 ton truck costs around DKK700 per hour

[3] It is interesting to note that one of the EU reports, "The efficient functioning of waste markets in the European Union: Legislative and policy options" talks about EPR (Enhanced Producer Responsibility) schemes being a problem when they imply monopoly power for the producer (p. 53).

2.2 C&DW markets in Denmark

Denmark is one of the leading EU countries in terms of construction and demolition waste (C&DW) recycling, surpassing the 70 % recycling target set by the EU's Waste Framework Directive. Already in the 1990s, recycling was over 90 % for C&DW. In recent years, recycling has dropped somewhat (to 87 % in 2015), due to growing concerns about hazardous substances in C&DW that require special treatment.

As shown in Table 1, Denmark generated 4.2 million tonnes of C&DW in 2015, excluding soil wastes (Affaldsstatistikken 2015). About a quarter of this was concrete waste[4] while wood waste and tiles and ceramics constituted 2.5 % and 1.9 %, respectively. (It is not possible to separate roof tiles from the aggregated "tiles and ceramics" fraction in the available data.)

Regarding treatment of these specific fractions, waste statistics do not provide information on treatment shares for each of the C&DW fractions. It can be assumed, though, that the main reason for not recycling the collected amounts is the presence of hazardous substances in the waste. In this report, it is assumed that the 87 % recycling rate for C&DW in 2015 is evenly distributed in all fractions (see TABLE 1 below), unless specific information can be retrieved. Specific data exists for concrete recycling, that reaches more than 90 % of the generation (MST, 2015).

TABLE 1. Recycling levels for C&DW, concrete, wood and tiles and ceramics wastes in Denmark, 2015

	Generation (1,000 tonnes)	Recycling (%)	Recycling 1,000 tonnes)
C&D waste	4,162	87 %	3,626
Concrete wastes	1,061	90 %	955
Wood wastes	107	87 %	93
Tiles and ceramic wastes	77	87 %	67

Waste statistics for 2015 include also a fraction called mixed construction and demolition waste that might include some quantities of concrete, wood and roof tiles. However, in this report, this fraction is ignored, as we investigate waste markets for source-separated materials. Mixed fractions are normally recycled by crushing and utilizing in lower level civil engineering applications, such as back-filling.

In the following chapters, the specific waste management flows for each of the three materials under investigation will be analysed in detail.

2.2.1 Description of the concrete waste market

Concrete is one of the largest fractions in C&DW, generating approximately 1 million tonnes of concrete waste each year. This quantity is based on the official Danish statistics; however, there are large quantities of concrete waste that are recycled on site in new buildings as filling material and these quantities are not registered as waste with the official register (ADS). Stakeholders place the unregistered quantities to at least as high as 1 million tonnes.

Concrete waste is normally produced by demolition and renovation activities (and to a lesser extent by new construction)) and is source separated from other waste materials. Demolition companies or dedicated waste collectors are in charge of collecting the waste and deciding on its treatment routes.

Recycling reaches over 90 % of collected concrete wastes (MST, 2015), amounting to around 955 thousand tonnes of crushed concrete in 2015 (see TABLE 1). It is important to note, though, that in Denmark practically all crushed concrete currently is diverted to recycling as sub-base material or (to a lesser extent) as filling material.

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[4] According to Miljøprojekt 1667, this includes only the reported quantity, while actual quantities could be twice as large.

Use of crushed concrete in new concrete as aggregate does not occur in large scale in Denmark for techno-economic and environmental reasons. Crushed concrete-based new concrete is currently more expensive than concrete based on virgin materials, so there is no economic incentive for waste operators to divert waste into that route. Moreover, for most concrete applications, legislative requirements on hazardous substances and quality standards discourage manufacturers from utilizing crushed concrete in their concrete products. Therefore, this treatment route has been followed only in demonstration projects or special cases where procurement rules required it.

On the other hand, lower quality concrete applications, such as tiles or block concrete elements face no legislative restrictions in terms of minimum performance requirements (standards), and are therefore promising options.

Currently, however, concrete waste is routinely crushed for use as sub-base or filling material, as the market for this kind of application works well. This means that waste collectors do not have an incentive to divert concrete waste from its existing routes unless the market conditions for a new alternative or for the existing market change.

TABLE 2. Market options for crushed concrete

Applications for crushed concrete	Product examples	Market functioning
Use in new concrete (under policy restrictions/standards)	Buildings and other civil engineering structures	No market at present
Use in new concrete (lower quality applications)	Concrete elements (e.g. tiles or blocks), fences, driveways	No market at present
Use as sub-base material	Roads, other paved surfaces.	
Use as filling material	Revetments, seawalls, embankments, etc.	

Strong market penetration
Limited market penetration
No market penetration

Overall, the demand for crushed concrete for use as filling material and especially as sub-base material is high, mainly because of the lower price of crushed concrete compared to the alternatives, but also because quality requirements for materials in this type of applications are not so stringent or specific. In contrast, stricter regulations, variability in quality, and uncertainty of supply limit the possibilities for crushed concrete to be used as aggregate in new concrete. In cases where the source of concrete waste is close to its final use (reduced transport environmental and economic costs) and the concrete waste is free from hazardous substances (low environmental and economic costs for pre-treatment), crushed concrete in new concrete is preferable (MST, 2015). But as these ideal conditions rarely occur in practice, waste operators prefer to use crushed concrete as filling or sub-base material.

TABLE 3. Prices per tonne for crushed concrete and natural aggregrates

<table>
<tr><th></th><th>Pre-treatment (DKK/tonne)</th><th>Transport (DKK/hour)</th><th>Crushed concrete (DKK/tonne)</th><th>Natural aggregates (DKK/tonne)</th></tr>
<tr><td>Clean concrete</td><td>85</td><td rowspan="2">35</td><td rowspan="2">65</td><td></td></tr>
<tr><td>Mixed concrete</td><td>160</td><td></td></tr>
<tr><td>Gravel</td><td></td><td></td><td></td><td>143-151</td></tr>
</table>

In general, the environmental benefits and burdens from recycling of crushed concrete varies greatly. As, both the secondary and the virgin aggregate materials are not based on energy intensive processes, the overall environmental impacts are not very significant. The preference, in environmental terms, for crushed concrete versus natural gravel or among the different treatment options for concrete wastes depends primarily on the transport distances between waste sites and new construction sites or between gravel pits and new construction sites.

Re-use of concrete elements is not part of this project's scope. Currently, re-use of elements is very limited worldwide and also in Denmark. The reasons are related to lack of knowledge and information on the concrete elements that arise as waste, the updated regulation around concrete elements that old concrete does not fulfil and the costs of processing. Some of these problems might be solved once the design-for-disassembly efforts become more common. But, given the long time span of buildings and concrete in particular, the re-use of concrete is expected to be limited for the short- and mid-term future, so it is excluded from this project as we scope only options that have the potential to offer a large scale solution for waste treatment. Using modular concrete and design for disassembly has been included as an option in the market simulation model to allow for exploration of possible future scenarios that include this path, but these scenarios are not explored within the scope of this report.

2.2.2 Description of the roof tiles waste market

TABLE 4. Market options for roof tile waste

Material and application	Examples
Re-use of masonry	Re-used entire masonry sections, lintels, etc.
Re-use of bricks and roof tiles	Cleaned bricks and roof tiles for new construction.
Recycling of crushed masonry	Crushing of bricks and mortar, firing and hardening to produce new bricks.
Recycling of crushed clay pipes, roof tiles, tiles and bricks	Crushed materials for surface covers, trails, possibly mixed with crushed concrete and asphalt
Recycling for green roof tops	Crushed brick distributed on green rooftops to enhance ability to absorb and supply water
Recycling for fills	Fillings in pipeline ditches, sub-base for tiles, capillary barriers, etc.

Source: Affaldsforebyggelse i byggeriet – forprojekt. Miljøprojekt nr. 1919. Miljøstyrelsen, 2017

Roof tiles constitutes a relatively small fraction of total C&DW. The total recorded waste in Denmark including bricks, roof tiles and other ceramics amounted to 77,000 tonnes in 2015. Unfortunately, there is no information on how much of this waste stream was roof tiles, nor what fraction of these were recycled or re-used. In this report, we assume a recycling rate for roof tiles equal to the overall recycling rate for C&DW, i.e., 87 %.

Roof tile waste is sometimes source separated (especially in renovation projects), but in many cases it is mixed with other ceramics, such as bricks and tiles and collected together. When collected together with other materials, the roof tiles are crushed and used as filler in road sub-bases and other civil engineering works.

When roof tiles are source separated and collected separately from other materials, there are two main routes for treating them: Direct re-use or recycling of crushed roof tiles. Crushed roof tiles are recycled mainly as drainage material, for example in tennis courts. The recycling route is the predominant option and it is safe to assume that most of the arising roof tile waste is recycled into drainage or filling material (together with other ceramics). Due to the increased cost of source separation and the demand for filling material (stabilgrus), it is safe to assume that most of the roof tile waste is recycled into the filling material.

Re-use of tiles occupies only a small portion of the roof tile waste. Re-use involves sorting and cleaning the unbroken roof tiles after a demolition or renovation or collecting unused roof tiles from new construction works (over-ordering). The re-used roof tiles are mainly used in roof repairs. Although a new construction could theoretically use re-used roof tiles, this does not happen in practice due to the absence of large quantities of roof tiles with the same type and design.

Figure 2.1below shows the main market options for roof tile waste. In market terms, the preference for an options (which determines the material flows in waste management) is influenced by the cost for obtaining a clean tile fraction upon demolition and the price this clean fraction can fetch. As most of the tiles are routed to the co-recycling together with other ceramics, we can assume that the common practice is to fulfil the minimum requirements of selective demolition and that there is hardly any economic incentive to further separate the roof tile fraction from the rest of the ceramics.

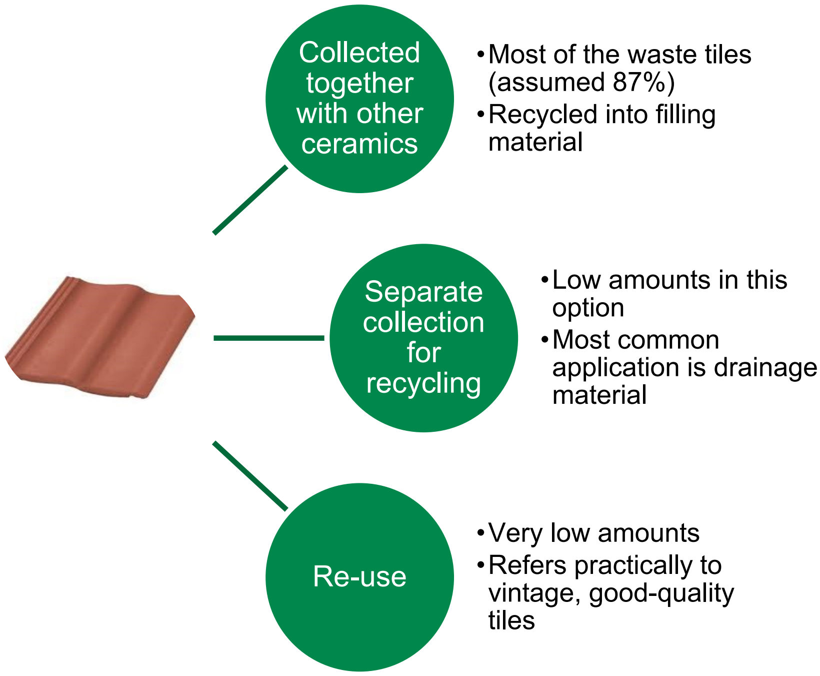

Figure 2.1 Current waste treatment options for roof tile waste in Denmark

Old roof tiles can easily have service lives of 300 years – much greater than tiles produced today (Vadstrup, 2012), so they are ideal for re-using. Although the tiles last for a long time on average, weaker tiles may erode, crack, or brake off during storms, making it necessary to replace or repair the roof much earlier. In case a roof is replaced, most of the existing tiles are therefore typically in good condition and could be re-used, perhaps as high as 50-80 % (Vadstrup, 2012). Old tiles have the advantage of having been tested in weather conditions over a substantial amount of time. Roofs made from new tiles need to be inspected regularly during the first decade or so for faulty or weak tiles that need replacing. This is not necessary for old tiles and thus constitutes a potential source of cost savings.

In spite of the clear advantages of re-using old roof tiles, the practice is not common in Denmark. When a new construction is made, time is of essence, so ordering new tiles that can be delivered quickly and reliably is often preferred. Moreover, the new tiles are inexpensive, making it difficult for re-used tiles to compete on price, as sorting and cleaning used tiles increases their cost. Moreover, owners of new buildings tend to prefer a roof made of uniform new tiles due to aesthetic reasons. The weathered and varied appearance of older tiles could be an advantage in some cases, e.g., in repairs of old houses or as an aesthetic element in itself. However, these cases are likely to constitute a niche market. Another barrier for re-use is that contractors tend to undervalue the gains of the durability, strength and reduced need for inspection of used roof tiles.

The table below lists companies and building materials retailers around Denmark that supply used roof tiles. According to these retailers, prices for re-used roof tiles varies a lot based on the condition, quality and design of each tile. Vintage roof tiles can fetch prices up to DKK 200 a piece, and the average price is around DKK 20.00 apiece. In comparison, the price of a new roof tile could be as low as DKK 10.00 apiece. This price range indicates that retailers believe that used roof tiles are mainly a niche market focused on old roof and are not suitable for large scale new roof projects.

TABLE 5. Danish suppliers of used roof tiles

#	Company	Place	Website
1	Tagstensdepotet	Svinninge	
2	Second Hand Tegl	Horsens	http://2ndtegl.dk/default.asp
3	Skave Nedbrydning	Holstebro	https://www.skave-nedbrydning.dk/vareliste/tagsten
4	Sanderum-Otterup Murerforretning	Otterup	http://www.fliser-tagsten.dk/fliser-tagsten/
5	Bergsten	Havdrup	http://www.bergsten.dk/
6	Jakobsen Tegl	København	http://www.jakobsen-tegl.dk/

Prices for the sale of crushed tiles used as filling material are not available.

Environmental benefits from re-use or recycling roof tiles are not significant in general, as the virgin material these replace is based on clay, which is a relatively abundant raw material and since the production of new tiles is not particularly energy intensive. On the other hand in Denmark, there is a scarcity of clay deposits (Vadstrup, 2012), so at a local level, re-use or recycling of roof tiles could yield measurable resource savings.

2.2.3 Description of the wood waste market

Wood wastes in C&DW is a relatively small fraction in terms of annual yields, reaching 107,000 tonnes in 2015. However, this quantity includes both impregnated and clean wood. Impregnated wood is considered hazardous and is not allowed to be recycled.

Since impregnated wood is used for outdoor wood constructions, a significant part of C&DW wood is impregnated, which can be recycled at relatively low levels (less than half was recycled in 2012[5]) For this reason, it is safe to assume that recycling of C&DW wood is at significantly lower levels than the overall C&DW recycling rate of 87 %, although precise recycling figures for C&DW wood do not exist.

The clean part of C&DW wood is collected through two main routes. First, wood is collected directly from demolition or renovation projects by dedicated collection companies. Contractors make sure that wood waste is source separated when the demolition or renovation work is performed. Second, private citizens or small businesses source separate wood from renovating private homes or offices and deliver the clean wood fraction to civic amenity sites. Waste collectors receive the civic amenity sites wood also and usually mix it with clean wood from other sources such as households (bulky waste). The treatment option for clean wood is mainly recycling, although there is some evidence that the final destination for some of the quantities is incineration as biomass (for exported wood)

The most widespread recycling route for wood waste is the production of chipboard. Kronospan is the only receiver of wood waste for this purpose in Denmark and it is able to receive around 220,000 tonnes annually (not only C&DW wood but also from household and industrial waste). This means that the amount of wood waste, separately collected from all sources (e.g. the dry wood from households, potentially available for recycling, is around 320,000 tonnes) might easily exceed Kronospan's capacity. Therefore, more and more wood waste is shipped for recycling abroad (mainly Sweden and Germany). Some recycling plants abroad, however, set strict requirements to the wood qualities they receive regarding the presence of hazardous substances in wood. Therefore, waste collectors in Denmark need to make regular tests to the collected quantities, which increase

[5] https://www2.mst.dk/Udgiv/publikationer/2017/05/978-87-93529-97-7.pdf

the cost of the recycling route. In general, a better sorting of wood during collection (e.g. avoiding impregnated wood) increases wood quality, its price and it improves the recycling potential significantly.

Another recycling route for wood is the production of pellets for use in gardens etc. This is relatively straightforward process for clean waste wood and the costs associated with it are relatively low. However, the occurring product is also relatively cheap and the demand at EU level is almost saturated (NL agency, 2013).

Wood has also a high heating value and does not generate fossil CO_2 when incinerated, which makes it a preferredfuel compared to the fossil alternatives. In a market perspective, incineration competes closely with recycling in terms of price. Since Denmark's recycling levels are much higher than the EU recycling targets, there is no direct policy incentive for increasing recycling quantities further.

Re-use or recycling of C&DW wood in new wood construction, although theoretically possible does not happen in large scale due to a variety of issues, as outlined in more detail in the following chapter. Small quantities of wood are re-used through building markets that typically focus on re-use of window or door frames. No data exists on the actual quantities of wood being re-used but these quantities are expected to be very low. Re-use of wood elements (e.g. beams) is also limited. Many environmentally aware companies operate within the wood market for buildings that could theoretically accept re-use of wood elements from demolished or renovated buildings. However, this market segment is not functioning well due to various reasons (see following chapter for detailed analysis) among which are the unsteady supply and the certification requirements that many of these companies have[6].

There are some initiatives in Denmark that have launched new products made of recycled C&DW wood (e.g. ReBlock produces wood tiles from waste wood and KKS Danmark produces insulation material from wood waste fibers) but these have a limited impact on the wood waste market as a whole. However, the conversion of wood into fibers can lead to many new ideas and innovations. So-called structural composite lumber (SCL) made from wood fibers is gaining increasing use in the United States (see, e.g., https://www.apawood.org/structural-composite-lumber).

[6] It is, for example, common for "green" wood suppliers to have a cradle-to-cradle certification that requires full transparency on the raw material composition, which waste wood cannot comply with or (in case one wants to analyse fully the composition of waste wood) it would increase the cost of re-use quite significantly.

3. Barriers

3.1 Method for identification of barriers

In this section, the identified barriers for further development of the three building material markets are presented. As expected due to the similar source and nature of the investigated materials, many of the barriers are common for all materials, but some are specific to each material. Moreover, the importance of each barrier might change according to the material in question[7].

Barriers are identified based on three processes:

1. Interviews with stakeholders (for more details on the interviews, please see Annex 4)
2. Analysis of case studies from Denmark and abroad (see Section 4)
3. Expert judgement from the project team.

Each barrier is analysed in terms of its influence on four specific market factors: price, availability, quality, and willingness-to-consider (W-t-C).

Price is traditionally considered the most important factor in market studies, but our investigations have revealed that the three other factors are also very important in C&DW markets. The price in this analysis mainly refers to the costs of processing and distributing the waste material that determine the final price to a consumer.

Availability has two dimensions which are distinguished in the modeling effort in Section 6: **Variety** or **scope** refers to the range of different designs or variants of the product, while **security of supply** refers to the consistency and average delay in delivery. Both affect the ability of waste product markets to cover demand in any given point in time. Contrary to virgin material-based products, waste materials cannot be ordered on demand but are based on the (stochastic) nature of demolition or refurbishment activities. The importance of scope is likely to be most significant for roof tiles and wood markets where the specific form factor, color, etc. is likely to be very important compared to concrete aggregate, which is a more homogenous product. Given the time-sensitive nature of construction projects, a reliable delivery is a key value driver in all cases.

The **quality** of the waste-based material refers to its technical properties, such as strength, durability, purity, consistency etc. These characteristics are likely to strongly influence the relative functionality and thus the value of the waste-based product in its final use.

Finally, the factor **W-t-C** expresses customer attitudes towards relatively unknown and unproven waste-based alternatives to existing products. It encompasses the stakeholders' established trust in existing products given a natural skeptical "wait-and-see" attitude in the industry. If customers are either unaware of these alternatives or if there is relatively little established information on their quality and reliability, they are likely to perceive them as being less attractive.

[7] For example, the cost of processing, depending on what share of the final price it entails, varies for concrete, wood and roof tiles.

3.2 Generic barriers

As generic barriers, we consider barriers that hinder the development of a market and are common for all materials in question. As mentioned, the effect of each barrier differs according to the material in question and this will be reflected in the analysis. TABLE 6 provides an overview of the identified generic barriers and their effect to each market parameter[8].

For example, the security of supply, meaning that the response to the demand might not be timely due to the uncertainty of when demolition or renovation projects take place, affects the stakeholders' W-t-C: the buyers of construction materials need to be certain that they will have the materials they need at the appropriate time so that their projects are not delayed and their costs increase.

TABLE 6. Identified generic barriers and their effect

Barrier	Description	W-t-C	Availability	Quality	Price
Certification scheme for waste products	Lack of certification increases uncertainty around waste materials	x		x	
Security of supply	Low level of response to demand because of lack of timely delivered waste material	x	x		
Cost of processing, storage and transport	Entails all costs for upgrading a waste material into a new product				x
Presence of hazardous substances	This results in lower overall quality or to increased cost of processing	x		x	x
Data scarcity	Lack of data leads to lack of market information such as size, potential etc.	x			
Lack of knowledge-awareness	Many actors in the branch are not aware of product alternatives that originate from waste	x			
Conservativeness of existing markets	The existing C&DW markets are inherently conservative and risk averting, therefore new products face scepticism	x			
Lack of generic examples and showcases	Current and past demonstration projects were perceived as case-specific and unfit for generalisation	x			
Lack of match-making	There is no widespread platform/initiative that matches supply of waste materials with demand for raw materials		x		
Insufficient selective demolition	Selective demolition so far does not deliver the quality and purity of waste materials necessary for them to be competitive in a waste market			x	x
Unwillingness to pay more for greener products	Stakeholders in the sector consider costs to be the most important decision parameter and the environmental aspect is ranked rather low among the factors shaping decisions	x			
Lack of documentation	Lack of documentation such as guarantees, labelling etc., reduces the perceived quality and standardised function of a waste material/product	x		x	

3.3 Barriers for concrete wastes

Figure below summarises the identified barriers in developing an effective market for re-use/recycling, for concrete wastes specifically. It also presents some ideas for alleviating the barriers, but this discussion is analysed in details in section 5.

[8] The identified barriers are listed in a random order and not according to their importance.

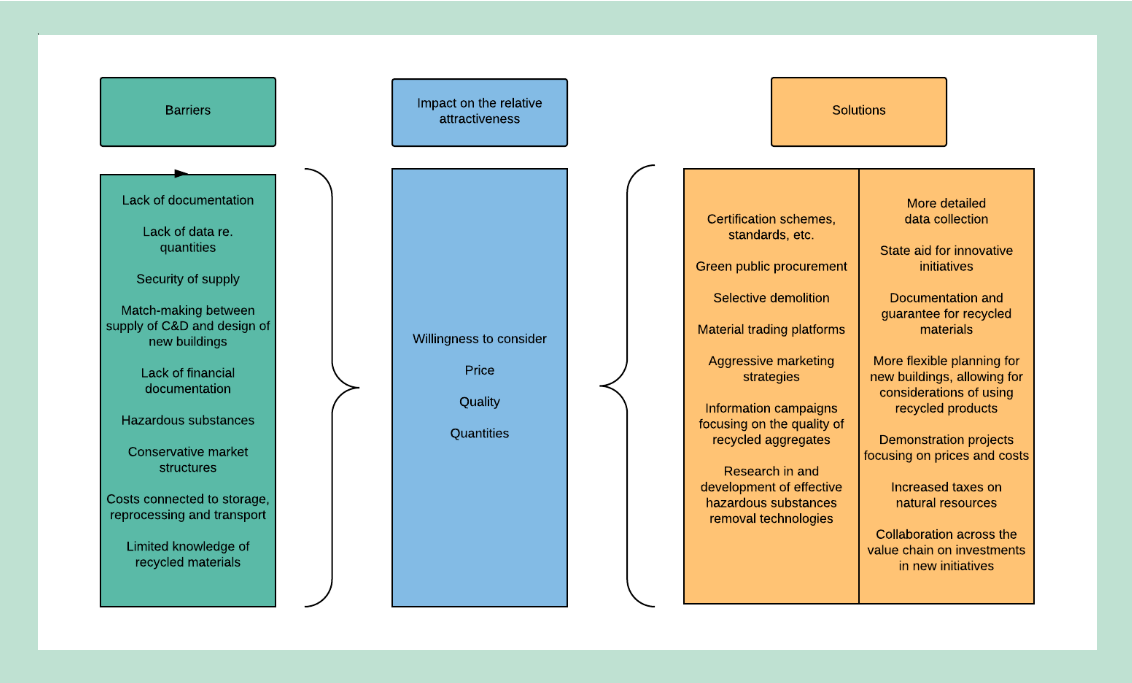

FIGURE 1. Barriers and solutions for further development of the concrete waste market

3.4 Barriers for wood wastes

Similarly as for concrete, wood waste barriers in developing an effective market for re-use/recycling, and solutions are presented in FIGURE 2.

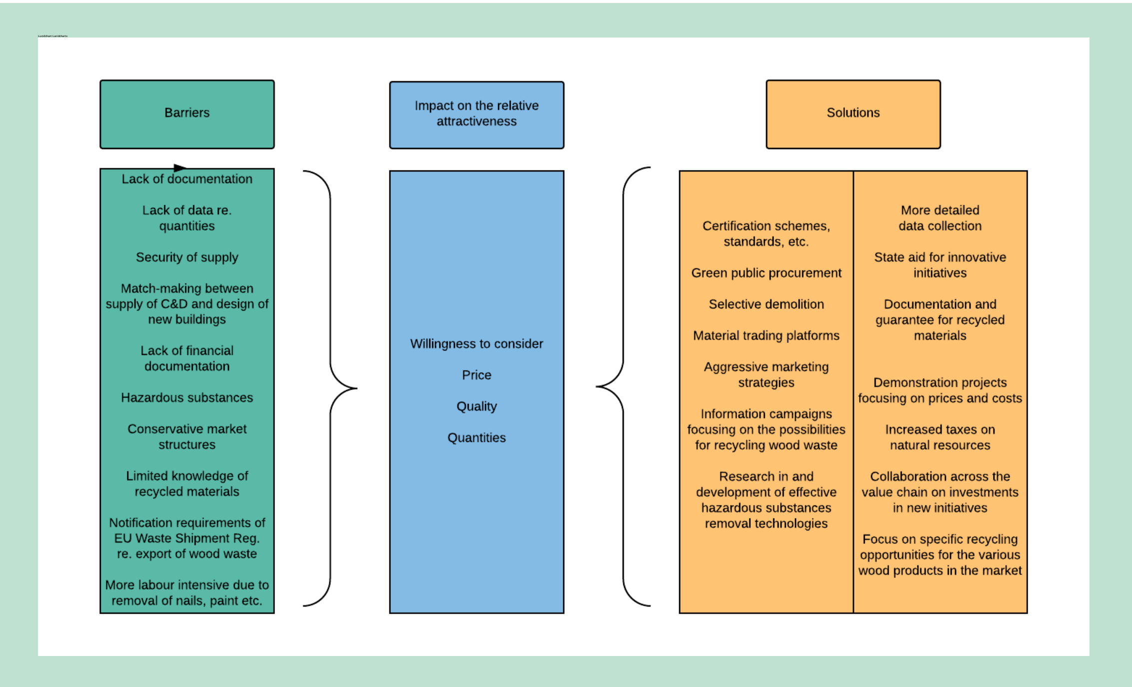

FIGURE 2. Barriers and solutions for further development of the wood waste market

Besides the generic barriers, the case of wood wastes has some material-specific barriers also.

TABLE 7. Identified barriers and their effect for wood wastes

Barrier	Description	W-t-C	Availability	Quality	Price
Administrative burden from notification process when exporting	Wood waste is considered as "green-listed" waste according to EU's waste shipment regulation. Since a lot of wood waste is exported for recovery and/or processing, the notification procedure when exporting is an extra administrative burden		x		x
Labour-intensive processing of cleaning up wood wastes from screws, nails etc.	The removal of impurities (e.g. nails, screws etc.) from wood waste requires a lot of manual labour which increases significantly the cost of processing				x

3.5 Barriers for roof tile wastes

FIGURE 3 below shows the barriers in developing an effective market for re-use/recycling, and potential solutions identified for the case of roof tiles waste.

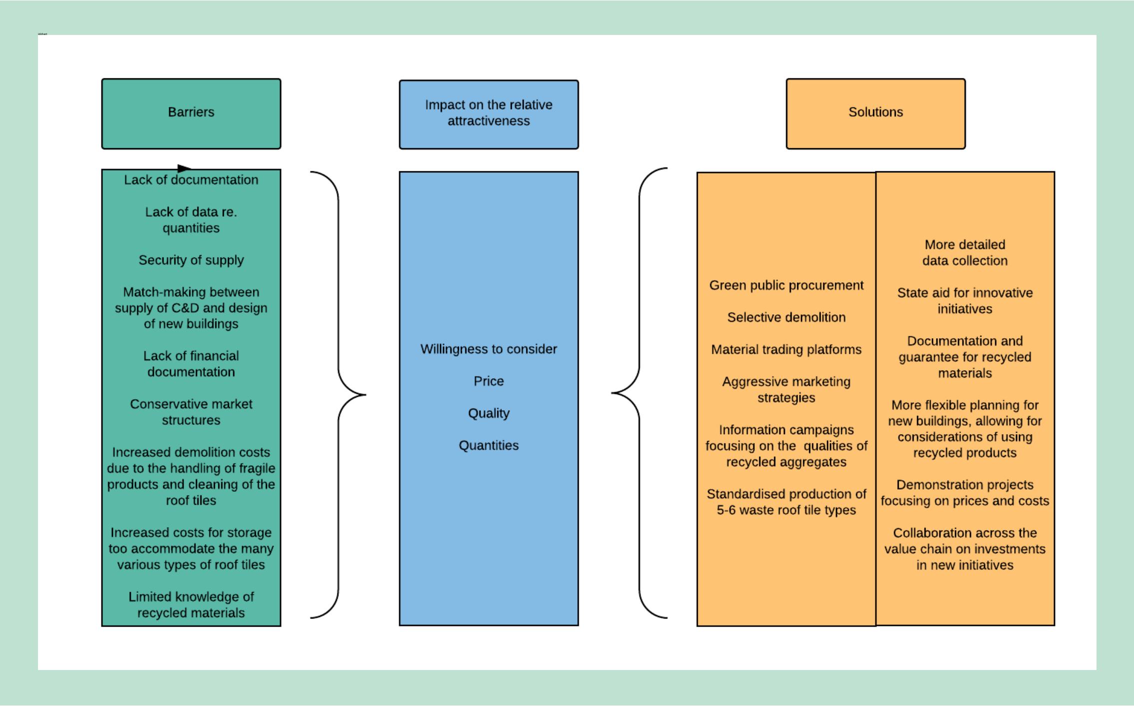

FIGURE 3. Barriers and solutions for further development of the roof tiles waste market

Besides the generic barriers, the case of roof tiles wastes has another material-specific barrier:

TABLE 8. Identified barriers and their effect for roof tiles wastes

Barrier	**Description**	**W-t-C**	**Availability**	**Quality**	**Price**
Cost of separating and cleaning individual roof tiles	In order to be able to re-use them, roof tiles need to be separated from other wastes and cleaned individually				x
Existence of too many types of roof tiles	The existence of various roof tiles makes it difficult to standardise their re-use and increases the need for storage so that security of supply is achieved		x	x	

4. Case studies from Denmark and abroad

Under this project, case studies from Denmark and abroad are analysed in order to:

- identify barriers for the further development of building material markets in Denmark;
- analyse potential solutions in the form of proposals for improvement that could be implemented in Denmark;
- understand the potential for improvement that the existing markets in Denmark have.

The main focus of the case studies analysis is to examine if there are markets in other countries that function well: markets that are open to innovation, pursue the development of secondary products that have a better environmental performance and offer acceptable market conditions to different waste products. If such cases are identified, the transferability of knowledge to Denmark should be investigated and appropriate proposals should be drawn.

It should be noted that not only successful case studies are to be selected, but failed ones too. The latter could be useful for understanding better the barriers to an effective market.

The list of case studies presented here is not exhaustive but indicative and representative of the efforts undertaken both in Denmark and abroad.

4.1 Presentation of Danish case studies

4.1.1 The recycled house in 1990s

The Danish recycling effort on concrete wastes started in 1980s when methods for recycling into filling material or road sub-base were developed. After a series of positive results in testing, the Danish Concrete Association established in 1987 a working group with the aim to formulate a methodology for utilizing crushed concrete in new concrete of a passive environmental class in relation to the concrete standard DS411. A technique was developed in 1989 after a testing period and it was decided to be tested in real life examples, namely in three "recycled houses" in Copenhagen, Odense and Horsens[9].

The recycled materials that were used in the three projects were, among others, wood and concrete. As a result from the application, it was concluded in 1996 that it is possible to build based on recycled materials both technically and financially.

More specifically, in terms of concrete, it was concluded that:

"Manufacturing of concrete with crushed tiles and concrete according to the Danish Concrete Association reference nr 34, has caused no problems and the workers have not observed any significant difference compared to working with conventional concrete."

It is also concluded that "an important prerequisite for recycling of building materials, in relation to similar conditions in other construction processes, is to develop standards and set up criteria for their utilization in practice". Moreover, there is a need to "create stock and secure the supply of recycled material so that the delivery can occur with a reasonable flexibility and in competitive prices."

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[9] source: genanvendelsesindsatsen i bygge- og anlægssektoren 1986-1995. Erik Lauritzen; Demex Ingeniører for Miljøstyrelsen, 1996.

However, the market conditions in the 1990s shows that there was a high demand for crushed concrete for filling material applications, so that recyclers could deliver all of their clean concrete wastes in that market. This limited the incentive for using crushed concrete in new concrete production.

4.1.2 Gamle mursten (niche product)

Gamle Mursten is a company that has specialised in reusing bricks from demolished buildings erected before the 1960s so that the walls were built with lime mortar. Walls erected later are based on a mortar mix of lime and cement and are therefore more difficult to separate the bricks during demolition.

The company has developed a method for removing the mortar from used bricks through the use of vibration technology. The process has no demand for water or chemicals. However, this can be applied only to older buildings, therefore the large-scale potential application is limited and the reused bricks are named a niche product.

Currently, Gamle Mursten processes around 45 million used bricks, according to Sidse Zimmermann. However, the prospects for further expansion are limited as the building stock of buildings before 1960s is declining.

4.1.3 Gen Byg Data Skive

The municipality of Skive, with the support of the Midtjylland region and the partnership of businesses has launched the Gen Byg Data project. The project objective is to create a data bank with the registration of re-usable or recyclable materials in the existing building stock and information on their quality, security and environmental hazards.

In this way, building owners and contractors can make use of this information when designing new buidlings with a view to make use of buildings about to be demolished. The data bank can therefore create value for the entire building value chain: building owners, architects, workers and demolition firms.

Currently, the project has registered five buildings that were about to be demolished. There is the aim that, in the future, all buildings will be automatically register as BIG DATA with the background of the information already registered under BBR. The database is handled by Dansk Genbyg which is an internet portal for selling of materials from recently demolished buildings. Users can register materials for free in the portal and Dansk Genbyg receives a small share of the selling price.

Multiple stakeholders were involved: Erhvervsakademi Dania, Nomi4S, Skiveegnens Erhvervs-og Turistcenter samt virksomhederne Dansk Genbyg, 4greenArchitecture, RGS 90 A/S og Salling Entreprenørfirma A/S.

The project identified the following barriers for the idea's further development:

- Attract the attention of stakeholders interested in secondary materials
- Missing municipal policies on recycling
- Missing information on hazardous substances in reused/recycled materials
- The legislative framework is not at the moment built around the circular economy
- Missing information on materials' quality
- New solutions have difficulties challenging existing practice
- Missing categorization and characterization of recycled materials
- Missing automated databases

The project report also identified potential solutions:

- Promote cooperation and knowledge sharing among the municipalities' departments
- Make the municipality a mediator for information, consultancy and further development of the project
- Bring in expertise
- Make the model more business oriented
- Create stakeholder networks

4.2 Case studies from abroad

Case studies identification could work as inspiration for Denmark. Ideally, useful case studies are the ones that demonstrate that an effective market for concrete/roof tiles/wood has been established at a large scale (nationally or regionally). Unfortunately, we have not been able to locate such a case in Europe. For example, even in the Netherlands, where promotion of recycled aggregates in new concrete has historically been very strong, recycled concrete has been able to reach less than 20 % market share.

Results from desk research

- Numerous case studies exist in Europe about demonstration projects, i.e. new buildings based on recycled materials. These are microscale applications that the willingness to use recycled material surpassed all barriers (costs, etc.)
- The Netherlands concrete case: In NL, they recycle the aggregates part of crushed concrete into new concrete and the cement part they use as sub-base material. This means that the concrete produced from recycled aggregate, needs more cement which makes it more expensive and more environmentally impactful than conventional concrete. But the system works because of government subsidy and the long transport required for primary aggregates. The government decided to do that because NL is running out of natural aggregates for concrete. This might as well be the future for DK, as we are running out of the good quality aggregates for concrete production (the lower quality aggregates for sub-base material are easier to come by). But for such a market to work, the DK government needs to stimulate it through tax deduction, subsidies etc. In the Netherlands, this situation with promoting recycled aggregates in concrete probably has some spin-off effects: companies trying to develop technologies for improving costs, quality etc. of the recycled aggregates (e.g. http://www.c2ca.eu/activities/)

We have also focused on case studies that demonstrate that specific identified barriers can be overcome. Learnings from case studies are:

- Technological developments in Europe can help with better sorting of C&DW (e.g. https://zenrobotics.com/) or more efficient processing (e.g. https://www.slimbreker.nl/). These will increase the quality of the waste products and maybe reduce the costs.
- Demonstration projects on cost-effective ways to include recycled material in new buildings exist (e.g. http://www.c2ca.eu/activities/, Venlo city hall)
- Not much good experience exists with taxes on natural aggregates (e.g. UK levy on natural aggregates)
- Many cases of countries or regions developing standards and certification schemes (mainly for concrete) (e.g. https://shop.austrian-standards.at/action/de/public/details/537192/OENORM_B_3140_2015_03_01, https://www.gov.uk/government/publications/quality-protocol-production-of-aggregates-from-inert-waste, UK standards for RCA BS 8500-2)
- Many cases of match-making platforms (e.g. http://recycling.or.at/rbb/cake_rbb/)

Again, no case study demonstrated an effective market for waste wood or roof tiles in Europe. The only (more or less) successful case for a concrete waste market (other than recycling it into filling material) is the Dutch case study presented below.

4.2.1 Theo Pouw Groep

Theo Pouw Groep is a Dutch company that receives and processes C&DW and sells secondary products. Among others, the company processes crushed concrete into secondary aggregates and they produce new concrete with it.

Contrary to other European countries, the Netherlands has limited access to naturally occurring sand and gravel and the demand for filling material and aggregates is mainly covered through imports and recycling of C&DW.

Similarly to Denmark, a large part of reclaimed concrete waste is used as road sub-base. Figures from 2012 show that around 64% of concrete waste was used as filling material or road sub-base while around 17% was landfilled. In 2012 also, around 300,000 tonnes (or 19% of generated waste) was recycled into the concrete branch.

Method

The clean heavy fraction of crushed concrete can be used as aggregate material in new concrete. First, the concrete is crushed typically into grain sizes of 0-32 mm. The metal parts are then removed through magnets and the light fraction such as wood and plastic are blown away. The aggregate is separated into a sandy fraction and one to two stony fractions.

5. Idea catalogue

This idea catalogue presents proposals that aim at improving the market effectiveness for selected C&DW materials (wood, roof tiles and concrete). Each of the proposals targets a market parameter (quality of product, willingness to consider the product, price and availability) and in this way, improves the market acceptance for a recycled/re-used building material. The proposals of the catalogue are then modelled in an economic model, specially developed for this project, that allows for the simulation of the market development if the proposals are implemented. The modelling is based on the proposals' influence on the modelling parameters.

The tables below show, in thematic groups, the idea catalogue proposals, which materials these refer to, which modelling parameter is affected and an evaluation of the proposals' effectiveness in creating an effective market for recycled/re-used building materials.

5.1 Documentation and regulation

Initiatives described in this section are related to administrative processes that ensure quality and performance of waste materials to interested buyers. As we have identified the perceived quality of waste materials to be an important overall barrier, initiatives that address the issue directly affect the stakeholders' "Willingness to Consider" (WtC). (For further details of this idea, see the model description in Appendix 1 and Section 6 below.)

All proposals under this grouping (listed in the table below) aim at reducing or alleviating the competitive advantage of virgin products compared with products originating from waste. Virgin products are based on raw materials that are delivered under strict specifications and standards. Virgin raw materials are based on lean production which guarantees homogeneity, fulfilment of minimum standards and minimum quality. Many of the virgin products have entered certification schemes and provide guarantee for the desired function and performance. The listed initiatives below aim at levelling the playing field, in this context, between virgin- and waste-based products.

Documentation and regulation					
Initiative	**Material concerned**	**Description**	**Barrier addressed**	**Affects**	**Actor**
Certification schemes	All	Incorporate the use of recycled materials in certification schemes such as DGNB. This would increase stakeholders' trust in the recycled materials. It would as well increase the quality of the secondary materials as a widespread use of recycled materials will enhance the product development. It is however important that the requirement for use of recycled material should be confirmed by EPDs (environmental product declarations) and LCAs rather than a fixed percentage as this could have a negative effect on the quality.	Lack of certification schemes for recycled products	WtC, Quality	The branch organisation Green Building Council is developing the Danish version of DGNB with involvement of actors in the building sector
End-of-Waste Criteria	Wood	End-of-waste criteria for wood would facilitate the cross-border trade of wood within the EU, as it would avoid the requirements of the Waste Shipment Regulation (Transportforordningen) At this point, only the wood fraction is exported for recycling.	Costs and administrative burden from Waste shipment regulation	Price	Government
Material Passport	All	A material passport contains all relevant information on the material's properties such as chemical composition, functional properties (strength, insulation, heat resistance etc.)	Lack of information on hazardous substances	WtC	Waste operators, companies that develop new recycling products
Guarantee	Roof tiles, wood	Provision of guarantee for recycled products would increase stakeholders' trust on the products and also they would be able to compete in equal terms with their virgin alternatives	Lack of guarantee for recycled products compared with virgin products	WtC	Waste operators, companies that develop new recycling products
Green Public Procurement	All	A focus on recycled materials in public procurements will open the market and affect the willingness to consider of commercial owners as well. Again, the requirement for use of recycled material should be validated by EPDs (environmental product declarations) and	The current market is conservative: stakeholders unwilling to accept change and negative attitude towards innova-	WtC	Government

		LCAs rather than a fixed percentage as this could have a negative effect on the quality.	tive products		
Revise Standards	Concrete	Experience from the business case of 'Gamle Mursten' shows the importance of a CE/ETA certification. The current version of recycled aggregates standards is not a sufficient driver for uptake of recycled concrete. Revision of standards with a focus on technical properties (more flexibility etc.) and not necessarily on the maximum allowed percentage will increase trust on the recycled products.	Conservative market, lack of perceived credibility of recycled products based on concrete	WtC	Government

5.2 Technical and technological advancements

The second group of initiatives refers to technical and technological advancements that can remove various barriers that hinder further uptake of waste-based products by the markets.

The security of supply is acknowledged as an important overall such barrier. Besides the inflexibility of waste materials supply (depending on demolition or renovation projects), new buildings' planning is also relatively rigid in terms of time. More flexibility in that would increase security of supply. Match-making platforms would also address this barrier and also increase visibility for waste materials/products. A more systematic data collection would give potential investors in the waste markets a more complete picture of the market size and potential. Finally, technologies that can remove hazardous substances more efficiently from waste materials would reduce costs and make the waste products' prices more competitive.

Technical and technological advancements

Initiative	Material concerned	Description	Barrier addressed	Affects	Actor
Flexible planning for new buildings	All	In order to address the fluctuations of supply when dealing with recycled materials, the planning of new buildings should incorporate a flexibility towards the specifics of each material.	Security of supply	WtC	Architects, construction companies
Data improvement	All	Better data quality increases transparency and provides potential investors with valuable information on e.g. market size, turnover etc.	Data scarcity that hinders business planning	Price, Quality, WtC	Government, waste operators
Matchmaking platforms	Wood, tiles	Lack of security of supply is a major barrier for a better uptake of C&DW in new building projects. Matchmaking platforms aim at closing the gap between supply fluctuations and demand (commonly based on rigid planning). Moreover, storage is cost intensive for recycled products. Direct matching between supply of C&DW and demand for reused materials, can reduce storage and transport costs	Security of supply, costs of transport and storage	WtC, Availability, Price	Construction companies, architects, demolition companies, owners
R&D on hazardous substances removal technologies	Concrete, wood	The presence of hazardous substances reduces the quality of the recycled materials significantly as it restricts the use of the products. Removal technologies today are expensive and R&D on the area could cause savings and products of higher quality	Presence of hazardous substances	Price, Quality	Companies and public research institutes

5.3 Economic instruments

This group of initiatives aims at affecting the price and in general the cost situation of collecting and processing waste materials into new secondary products.

Initial investments for developing new waste-based products are relatively high (e.g. concrete waste processing plants, large storage facilities for roof tiles). A state support (in any form) would reduce the risk of potential investors linked with the initial investment. On the other side, a tax on natural resources would artificially increase the virgin products' prices and thus make waste products more competitive.

Another identified issue is that the relevant demonstration projects have historically focused on technical aspects and not on costs. There is also a common misconception that greener products cost more. Demonstration projects that address the cost issue could help increase the WtC of stakeholders towards waste products.

Economic instruments

Initiative	Material concerned	Description	Barrier addressed	Affects	Actor
State support for new initiatives	All	New products based on waste materials often require a high initial investment, mainly because of storage facilities and processing equipment. A financial scheme for support would alleviate these costs. Similar schemes exist (MUDP), but here we are calling for more custom-made support for the initial investment	High initial investment	Price	Government
Demonstration projects focusing on costs	All	So far demonstration projects in DK have focused on technical aspects. A demonstration that recycled material can be cost-efficient would encourage more support by project owners	Cost of processing, storage and transport	WtC	Owners, architects, construction companies
Tax on natural resources	Concrete	Taxation on natural aggregates increases the margin for profit when processing concrete into recycled aggregate.	Cost of processing, storage and transport	Price	Government

5.4 Other initiatives

The last grouping of proposals for initiatives includes all unclassified initiatives to the previous groupings. These range from information-spreading efforts (marketing strategies, information campaigns) to capacity building on waste issues in all stakeholders in the sector.

There are also material-specific initiatives: due to the many wood applications, niche-markets for re-use should be created (separately for floors, windows/doors and beams). On the other hand, in order to tackle the barrier of too many roof tile types, the standardization of 5-6 types would help reduce storage costs and make it easier to obtain documentation and guarantees.

Other initiatives

Initiative	Material concerned	Description	Barrier addressed	Affects	Actor
Aggressive marketing strategies	All	This initiative aims at increasing the knowledge and properties of new products put on the market (e.g. insulation material from wood waste).	Often actors are not aware of the recycled alternatives and even if they do, they do not have trust in the new product	WtC	Companies that develop new recycled products
Information campaigns	All	Inform stakeholders about properties of recycled products, mainly in order to avoid misconceptions	Often actors are conservative and inherently think recycled materials are inferior to their virgin alternatives	WtC	Companies that develop new recycled products
Selective demolition	All	Maximize the separate collection of C&DW materials and also separate them in different qualities	Increases security of supply, ensures quality and purity of material, (cost effective by reducing processing costs)	Price, Quality	Construction companies, demolishers, waste operators, government, owners
Support niche markets for wood sub-products	Wood	In order to promote re-use for wood waste, efforts should be different for floors, windows/doors, beams etc.. This presupposes selective demolition for separating the wood products.	Security of supply, presence of hazardous substances	Quality, Price, Availability	Companies that develop new recycled products
Standardize 5-6 waste roof tile types	Roof tiles	The focus on the most used 5-6 roof tile types reduces the storage costs and allows for re-use companies to respond to demand fluctuations	Too many roof tiles types exist, so storage costs increase and security of supply is at risk	Price, WtC	Companies that develop new recycled products, producers of construction materials
On-site recycling	Concrete	This applies to relatively large construction projects. Concrete from demolition is processed and used on site as input to ready mix concrete	Security of supply, cost of transport	Price	Construction companies, architects, demolition companies, owners
Capacity building	All	Actors in the building sector should increase their capacities and professional capabilities on C&DW management, management options, waste products and re-use	Lack of knowledge, awareness	WtC	Construction companies, demolishers, waste operators, government, owners

6. Modelling the C&DW markets

This section provides a brief description of the market simulation model. The model structure and equations are described in detail in Appendix 1 and Appendix 2.

6.1 Modeling approach and purpose

The market simulation model is based on a methodology called system dynamics, a quantitative method that uses dynamic models to simulate socio-economic systems.[10] One of the challenges of modelling markets that do not yet exist is that there is no history on which to base future projections. Hence, any analysis will contain a great deal of uncertainty about future demand, supply, prices and costs. Moreover, there may be factors affecting market performance that may not be available ever in a statistical form. For instance, conservative attitudes or beliefs of decision makers, or general skepticism towards new products, may be an important influence on the emergence of the market, yet may not be easy to measure or record. One is left, essentially, with having to make educated guesses about such factors.

The system dynamics method is designed to deal with this situation by using simulation to explore possible future scenarios in a structured manner, with an emphasis on explaining WHY certain outcomes appear, as opposed to the numerical details of WHAT they are.

The simulation model represents the future markets for the three waste fractions, concrete, wood and roof tiles. The elements that were thought to be of particular importance were:

1. Possible **learning-curve effects** on costs, allowing unit cost of recycled and re-used materials to decline over time with increasing industry experience.
2. **Scale economies**, where larger markets for distribution, storage, classification, and marketing would lower the average cost of recycled or re-used materials.
3. **Scope economies**, where a wider range of different products would afford a better match between the requirements of a specific construction project and the re-used materials available on the market. This is thought to be particularly important for the roof tile and wood market, since both of these materials would presumably retain much of their original form at the time of demolition. For the concrete market, where the waste product is crushed and mixed into a homogenous product, this is likely to be of less significance.
4. **Market learning and adoption**: A crucial factor in any adoption of new products and processes is the customers' awareness or **willingness to consider** the new alternative products. Given the importance of quality and timeliness of delivery in construction projects and the substantial financial risks involved of delays, poor quality, or environmental issues with problematic substances found in materials, it is not surprising that buyers may be skeptical of any new material source. In addition, the construction industry is more characterized by competition in cost, quality and timing than by product or process innovation, leading naturally to a more conservative attitude among its actors.
5. **Availability and security of supply**. Given that timeliness plays a crucial role in construction projects, the security of getting on-time deliveries is bound to play a crucial role in the performance of the market. Therefore, having sufficient supplies on stock will be a key success factor.

All of the factors mentioned above will in effect constitute a set of self-reinforcing mechanisms for the evolution of the market, as illustrated in Figure 4.. Lower cost from scale economies or learning curve effects, increased scope economies, increased market acceptance and security of supply through large-scale deployment and variety in goods supplies, all of these effects are in turn dependent upon a sufficient market volume: the greater the market size, the more these forces will work to improve the quality and attractiveness of the product, provid-

[10] For a comprehensive description of the system dynamics method, see Sterman, J.D. (2000) Business Dynamics: Systems Thinking and Modelling for a Complex World, McGraw-Hill.

ing the basis for further market growth. Hence, much of the purpose of the modelling has been to uncover these mechanisms and how policy or other measures may affect them.

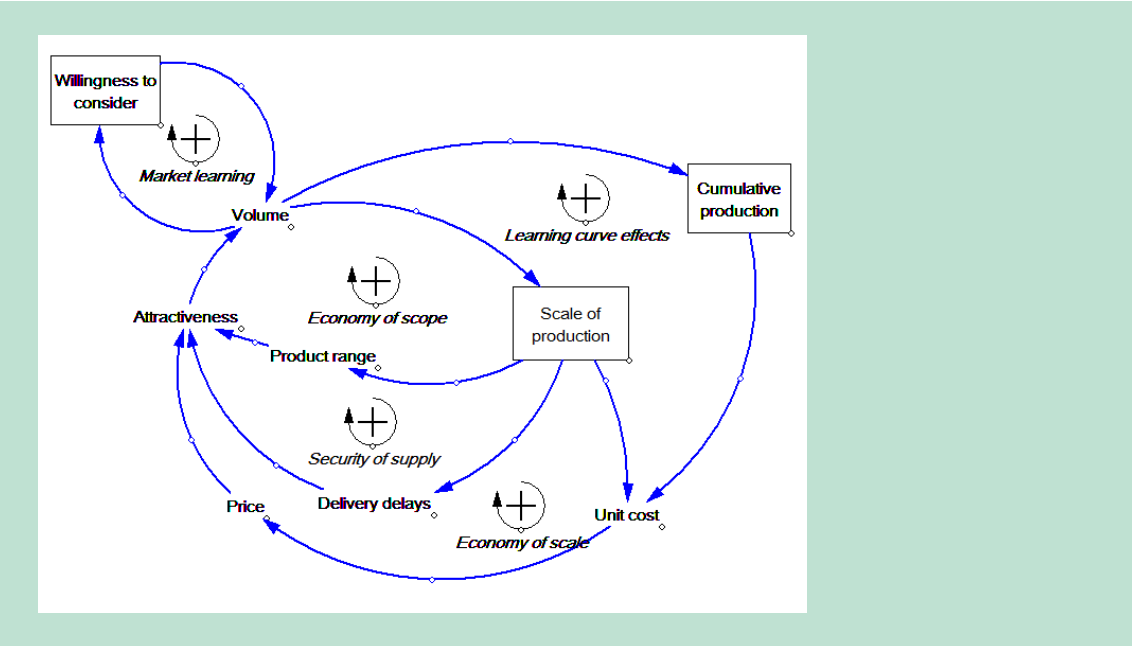

FIGURE 4. Positive (self-reinforcing) feedback effects driving market evolution

While these self-reinforcing feedbacks can be a source of momentum for change, they also represent a significant source of inertia which can delay the development of the market. This inertia is further exacerbated by the slow material flows involved in the system, as materials are embedded in physical structures and as distribution and processing capacity requires physical investments in capital. The model represents all of these flows explicitly, as detailed in Appendix 1.

In the case of concrete, the model distinguishes between the current state of affairs, where concrete is for the most part crushed used as filler material ("traditional disposal[11]"), versus the potential future use of concrete that is processed and recycled as aggregate in new concrete ("recycling"). As a potential further issue to explore, the model also incorporates the possibility of designing structures for disassembly and re-using modular concrete, though this part was not explored in the present project.

For wood and roof tiles, the model uses a somewhat simpler representation where materials that become available from demolition can either be re-used or disposed of in conventional ways (burned, or crushed).

6.2 Demand side of the market

As mentioned, demand for re-used/recycled material is influenced by four factors: price, quality, availability, and "Willingness to Consider" (WtC). The latter gets at the idea that the majority of market participants have a relatively conservative attitude towards trying out new products. Given the very substantial risks and potential liabilities involved in construction projects, buyers are reluctant to employ re-recycled or re-used products unless there is sufficient documentation, either in the form of product testing and certification or in the form of experience and reference value cases from other customers in the market. This introduces a classic self-reinforcing adoption cycle, often called "Word-of-mouth", where the number of market participants willing to consider the product is a function of the number of existing adopters, which is in turn driven by the number of new adopters, etc. etc.

[11] The phrase "traditional disposal" was chosen during the earlier part of the model development. As our understanding of the waste processing evolved, we realize that a better term might have been "conventional recovery".

The WtC is formulated as a dimensionless index between 0 and 1, where 0 represents complete lack of awareness and 1 represents a fully accepted product that is judged on par with the conventional alternatives. It is assumed to evolve gradually over time as a result of three processes: 1) Information campaigns or marketing efforts to raise awareness in the industry, typically initiated by government policy will raise it. 2) "Word-of-mouth" effects through direct contact or reference value cases from market participants will raise awareness, as a function of the market share of the new product, the intensity of contacts, and the degree to which such contacts lead to changes in behavior. 3) Awareness may erode over time to the extent that knowledge becomes obsolete or people forget.

While both the concrete and the tiles markets have active market learning (WtC varies over time), for the wood market, we have chosen to remove this effect by assuming that the market is fully aware of the properties and availability of the re-used/recycled products. The rationale behind this choice, apart from reducing the amount of complexity in the analysis, was mainly to explore some of the other dynamics in this market, related to economies of scale, for instance. As mentioned previously, the scarcity of data for the wood market means that the analysis has more the character of hypothetical "what if" scenarios than any operational forecast. The choice to remove the WtC effect means that results will be somewhat on the optimistic side.

Customers are assumed to compare the relative attractiveness of the recycled product to the conventional alternative. Attractiveness is a function of the relative price, the perceived relative quality, and the relative variety. The attractiveness is then "discounted" by the WtC factor to arrive at a perceived relatively attractiveness. The perceived attractiveness in turn determines the indicated market share of the recycled product, where a higher attractiveness will lead, other things equal, to a higher market share. The concrete shape of this market share function, as well as the sensitivity to price, quality and variety, are all set by parameters in the model, specified in Appendix 1.

6.3 Supply side of the market

Actual deliveries are further constrained by available supply. The supply side is modelled somewhat differently for the three waste fractions, reflecting the assumptions that different factors are at play in the evolution of the market for the three.

For all three sectors, supply depends on "capacity" (processing capacity, distribution logistics, marketing and administration, etc.). Investments in new capacity is driven by both "price signals" and "quantity signals". Thus, investors are assumed to come up with some notion of expected demand or output (the "quantity signal"), modified by an effect of the average profit mark-up (the "price signal"). A positive (above normal) economic profit will lead to a higher target output, and vice versa. Suppliers form expectations of demand based upon recent sales performance. Target capacity is further potentially constrained by available raw material from demolition, but is also influenced by high prices and profitability (the price signal).

In the short run, prices are assumed to reflect unit cost multiplied by a mark-up factor that reflects current demand-supply conditions, In the longer run, the unit cost of production is assumed to be affected by both scale economies and learning curve effects. Moreover, the model also includes the potential depletion of virgin aggregate resources for concrete (excavated gravel and sand). This can be significant to the extent that rising prices of virgin aggregate can affect the demand for recycled aggregate as an alternative (remember that demand is determined by the relative price of the two.) Given that sand and gravel is a non-renewable resource and that there are increasing signs of shortages of this natural resource, it is relevant to include this as a possible factor in the scenarios. The model operates with a fixed stock of virgin material resource that is depleted by whatever material is used in current production of new concrete that is not based on recycled aggregate. It is assumed that as this stock is depleted, the price of virgin aggregate will rise.[12]

[12] In the case of roof tiles and wood, virgin raw material, clay and lumber, respectively, is also a potential constraining factor. However, in the present study, these factors were not thought to come much into play within the time horizon considered in the model and were therefore ignored to simplify the modeling.

6.4 Proposals for consideration

In this section, we describe how four elements of the idea catalogue are implemented in the model. These four elements were selected as most effective in a meeting of the partnership for sustainable construction and waste prevention held in December 2017. In many ways, all four proposals implicitly aim to strengthen the self-reinforcing feedback effects at play in the development of the C&DW market, illustrated in Figure 4. To restate, the four initiatives deemed most effective by the partnership were

1. **Certification schemes, product warranties, and "material passports".** The rationale is that this would improve the confidence of buyers in the technical quality of the product, as well as minimizing perceived risks of either technical shortfalls or possible environmental problems.
2. **Matching and market-making trading platform.** The main purpose of this would be to heighten the visibility of secondary materials markets and improve the information efficiency of the market, leading to better allocations of materials to local customers, thus minimizing transportation costs. Moreover, the expectation is that the platform would increase the market volume, leading to lower costs and better scope economies.
3. **Demonstration projects with focus on costs and benefits**. The main purpose would be both to generate more knowledge of costs and issues in operating the market, and a documentation of possible benefits that would be directly relevant to decision makers on the demand side.
4. **Green public procurement**. Apart from signaling the importance of re-cycling and re-use and serving as a basis for gaining experience, the main effect would be to provide a minimum demand for secondary materials that could serve as a seed for the formation of a private commercial market.

The modelling scenarios explore the effects of each of these four initiatives by comparing them to a base case where no such initiatives are performed. The question of interest is mainly whether they are each sufficient to provide a turn-around of the market, or whether they need to be used in some combination.

The first three initiatives all work to bolster the confidence in the secondary materials and to provide better information on costs, quality, etc. In the model, this is interpreted as a factor that increases the Willingness to Consider factor among buyers and potentially also the perceived quality of the product, since certification allows for a better differentiation among products. This may be implemented concretely by interpreting the effort as a "marketing" or information campaign that adds to the WtC stock.

Certification schemes also serve to improve the actual quality in that it reduces the risk variability in the properties of the product, itself an important element of quality. In the model, this can be implemented as an increase in the quality factor entering product attractiveness.

There are of course also costs associated with the certification and documentation itself, and it may lead to higher discard rates of unacceptable products. As the cost and scale economy figures are already highly uncertain, we chose to exclude this additional effect from consideration at this stage.

To some extent, the second initiative, market matching platforms, also serves to lower average costs, both by minimizing average transportation, by minimizing the required inventory of material on hand to provide the same level of supply availability, and by providing a better match with buyer demands (quality): All other things equal, if it is easier to locate specific materials somewhere in the market, there is less chance of stock-outs for a given average level of inventory holdings. In the model, this is implemented as a combination of a lowering of the required inventory coverage to provide the same level of supply security and an improvement in average quality.

Moreover, the second initiative may affect the economy of scope effect on the market: with an efficient information exchange platform, the volume and inventory required to provide sufficient variety for customers may all other things be less when it is easy for them to locate specific items. This is particularly true if the system can to some extent be made forward-looking, anticipating the provision of used building components before demolition. In the model, this is implement as a reduction in the requisite scale to afford a given level of scope economy or variety.

Finally, the matching platform itself serves to enhance the visibility of the market, hence promoting faster market learning through the WtC mechanism.

The third initiative, demonstration projects with costs and benefits, creates more transparency in the market and provides documentation for proven results. In this manner, the main effect would be to raise market awareness and the willingness to consider the new products. Hence one would primarily implement this in the model by increasing WtC via the equivalent of a “marketing” campaign.

The fourth initiative, green public procurement (GPP), has a different effect in that it adds a less elastic component of demand for the secondary material. In the model, we accommodate this by assuming that a certain fraction of demand (GPP market share) is governed by procurement regulation and therefore is not sensitive to issues such as price, quality or delivery delay. Here, we are assuming that the basis of comparison is between the secondary material and the conventional alternative, not between alternative suppliers of secondary material, where there may indeed be competition in bidding for these GPP contracts.

For detailed specifications of the parameters and parameter changes involved, see Appendix 2 and Appendix 3, respectively.

7. Simulation results

This section presents some concrete numerical simulations of the scenarios and policy results. Appendix 3 lists the specific parameter changes involved in each simulation. It is important that the results not be taken too literally: Within the scope of this project, it has not been possible to verify all the parameters and the robustness of the results to changes in these. The main purpose of this analysis is to raise debate and consideration for further inquiry into promising policies and ideas for why they may or may not work as intended.

7.1 Reference case (no policies)

In the base case, we assume that there are no particular policy initiatives to enhance the development of the markets for secondary materials. For all three markets, we see a failure to materialize, though for somewhat different reasons.

7.1.1 Concrete recycled aggregate (RA) market

FIGURE 5 shows the result for the recycled concrete aggregate (RA) market. We see that, in spite of the attractive product (relative attractiveness of RA is greater than 1), the lack of market awareness (WtC) means that the positive feedback loops never have a chance to take off.

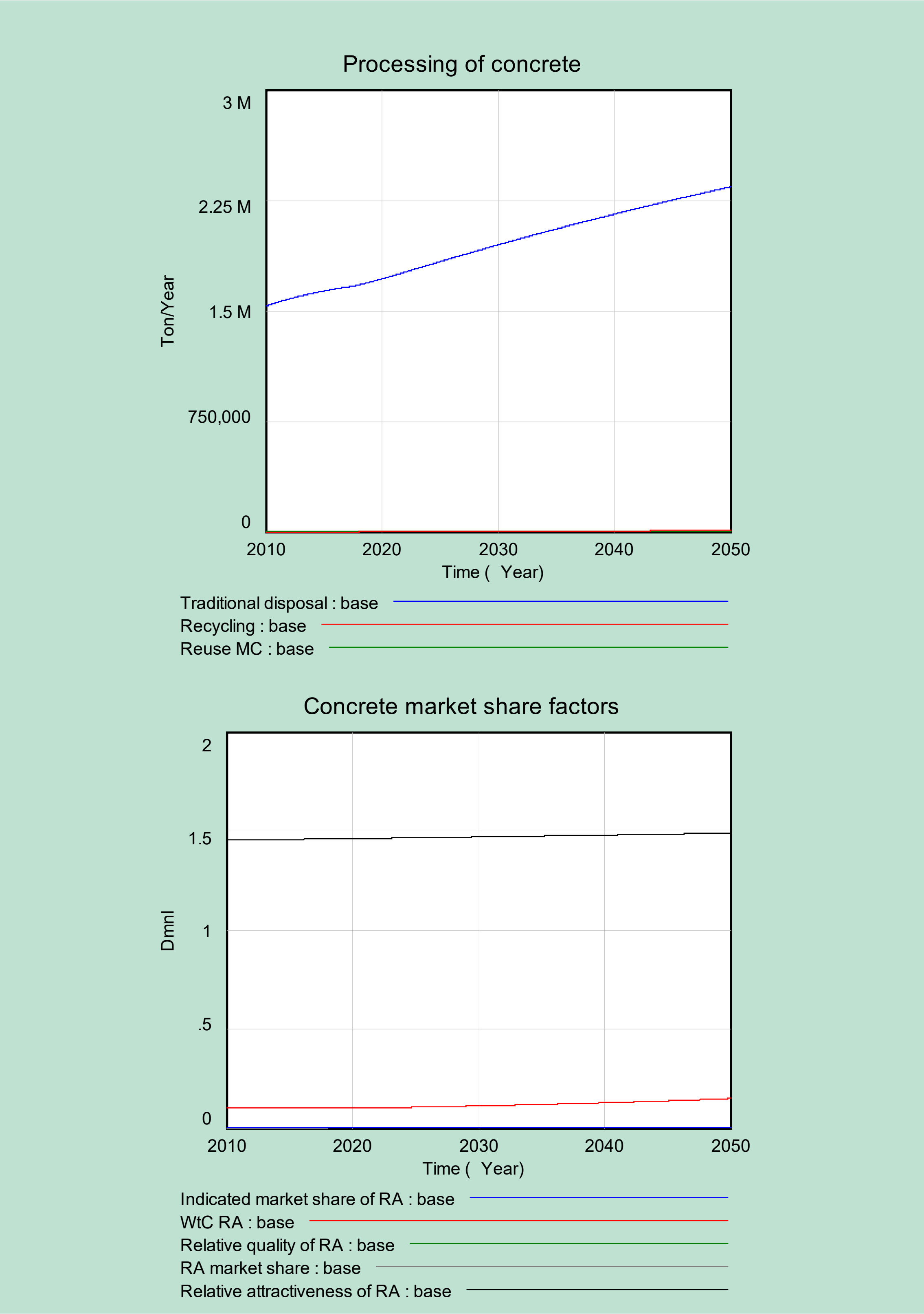

FIGURE 5. RA market, base run: No policy initiatives to enhance secondary markets

It is interesting to note that due to the self-reinforcing feedback effect related to market learning or Willingness to Consider (WtC), the market can exhibit tipping point properties. For instance, if one increases the initial WtC from 10 % to 20 %, the result is that the RA market will eventually take off and make the transition on its own, as illustrated in FIGURE 6. Note that the product is largely the same in both cases (compare FIGURE 5), i.e., the relative price, availability and quality is the same, but in the former case, there is insufficient market consideration to allow the word-of-mouth process to take off.

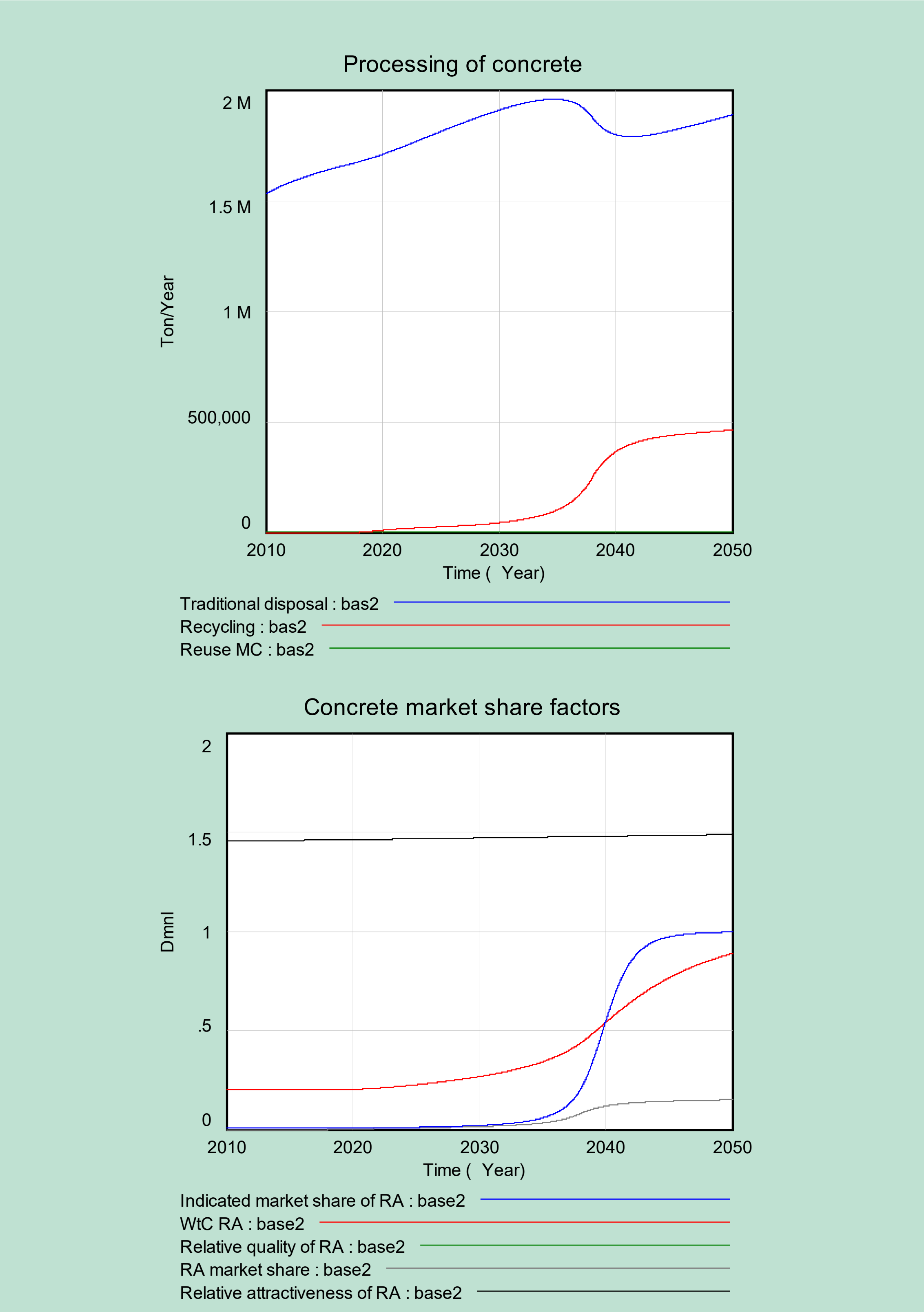

FIGURE 6. **RA market base run 2: As FIGURE 5 but with twice the initial WtC (20 %)**

7.1.2 Roof tile market

The roof tile market also fails to take off due to low market awareness (WtC). FIGURE 7 shows how low awareness prevents the market from gaining any significant share, even though the price, quality, and scope effects are all neutralized, meaning the product is equivalent to the alternative. Even though awareness is slowly rising, it never reaches a point where the positive word-of-mouth feedback takes off. (If you run the simulation out to the year 2100, you will find that the market eventually takes off.)

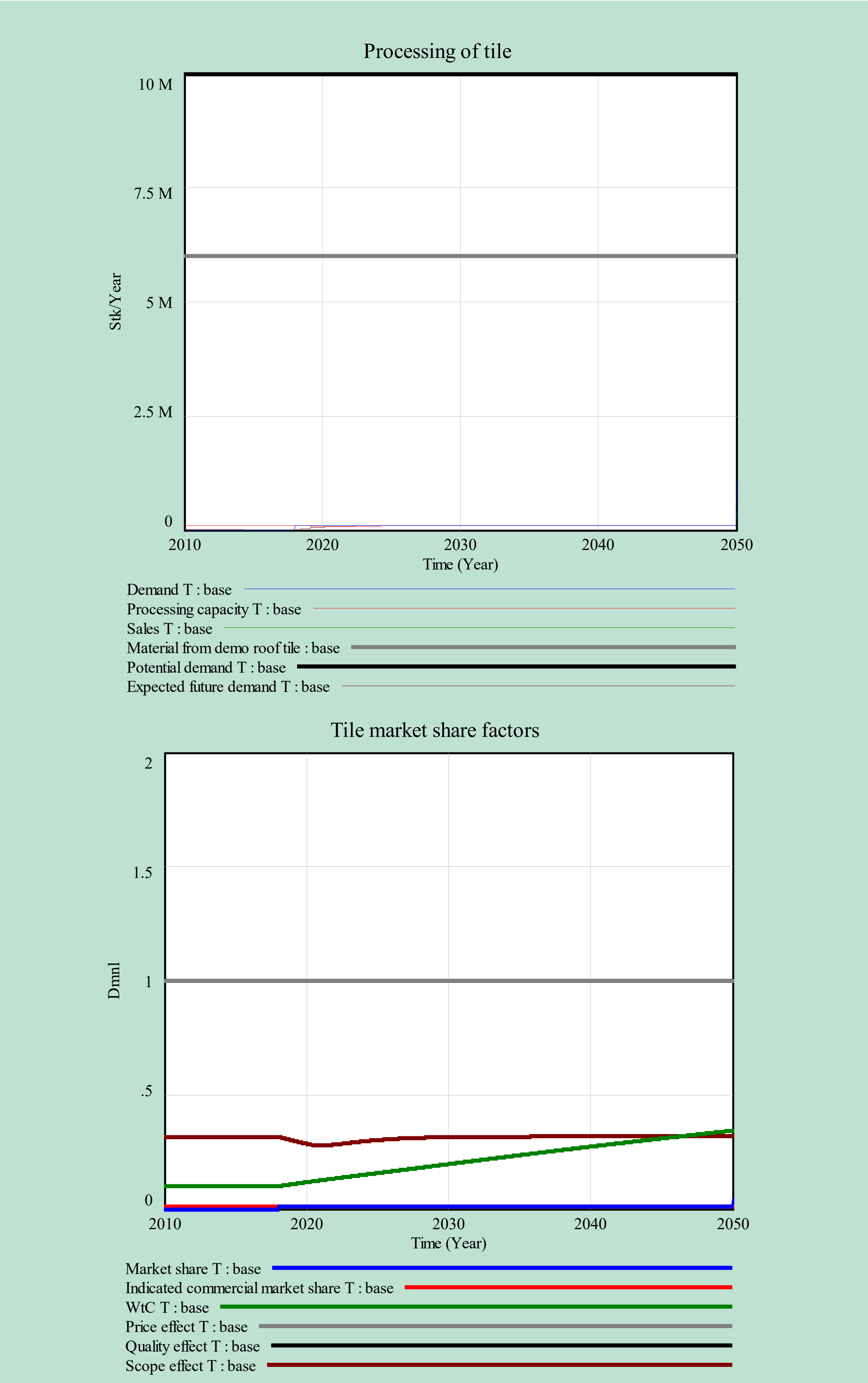

FIGURE 7. Tile market base run: No policy initiatives to enhance secondary markets

Moreover, the tipping point for the tiles market is much further off than for concrete. Raising the initial awareness level (WtC) to 20 % does not produce a transition. Indeed, one would have to raise awareness to 50 % to see a transition before the year 2050. The difference arises from the fact that the assumed need to carry substantial inventories of tiles effectively creates a delay in the system: The positive feedback from word-of-mouth takes much longer to operate, meaning there is less chance of a transition.

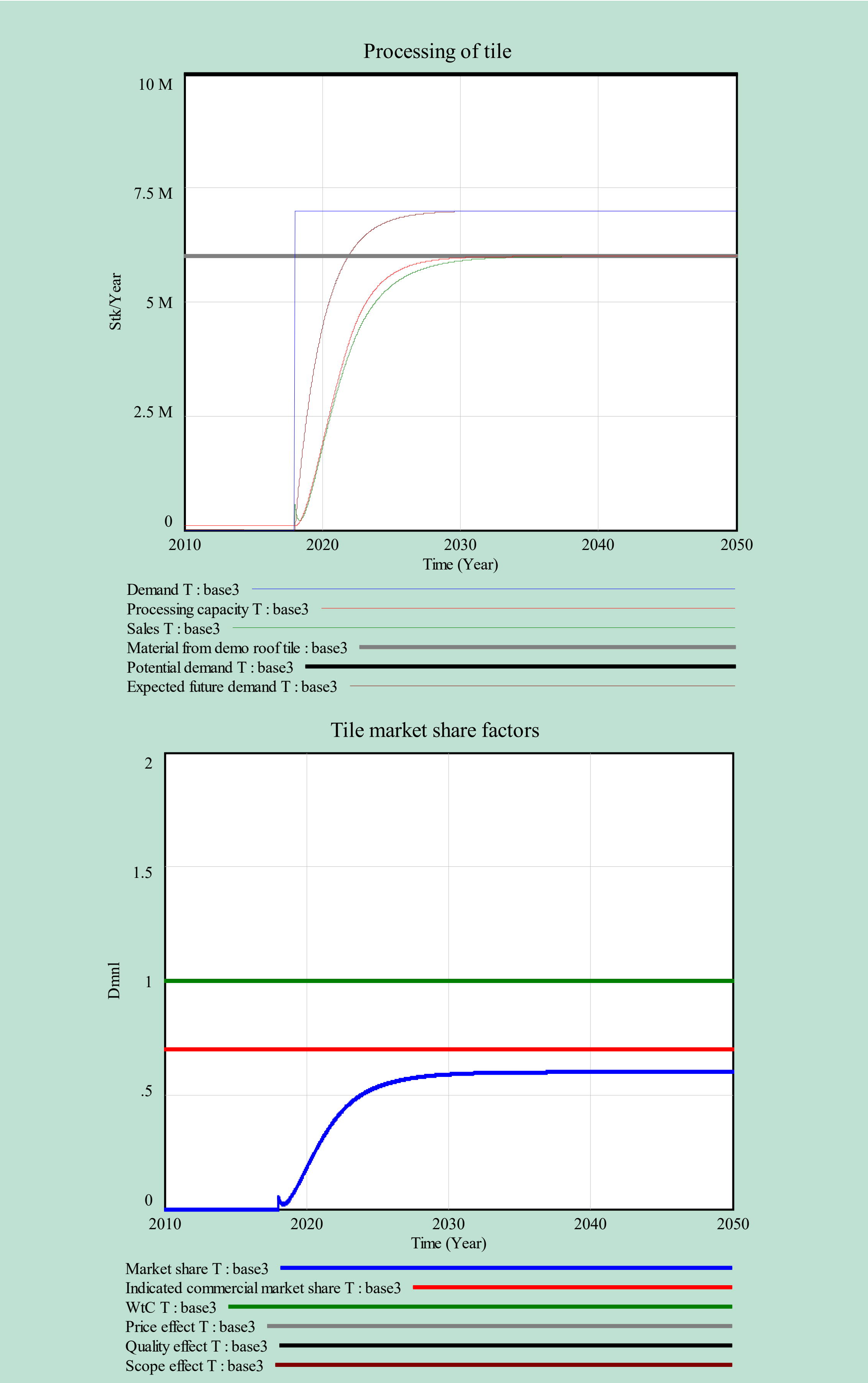

FIGURE 8. Tile market base run 3: As FIGURE 7 but with initial WtC for the tile market set to 100 %

If one eliminates the barrier by setting initial awareness to 100 %, a transition does indeed occur fairly rapidly, as illustrated in FIGURE 8. On the other hand, none of the other barriers have been activated at this stage. If, for instance, we activate the economy of scope mechanism by setting $\rho_T = .5$, we see that the lack of sufficient range and selection makes the product sufficiently unattractive that the market never takes off (See FIGURE 9).

All in all, this indicates that there is likely to be a need for policy intervention.

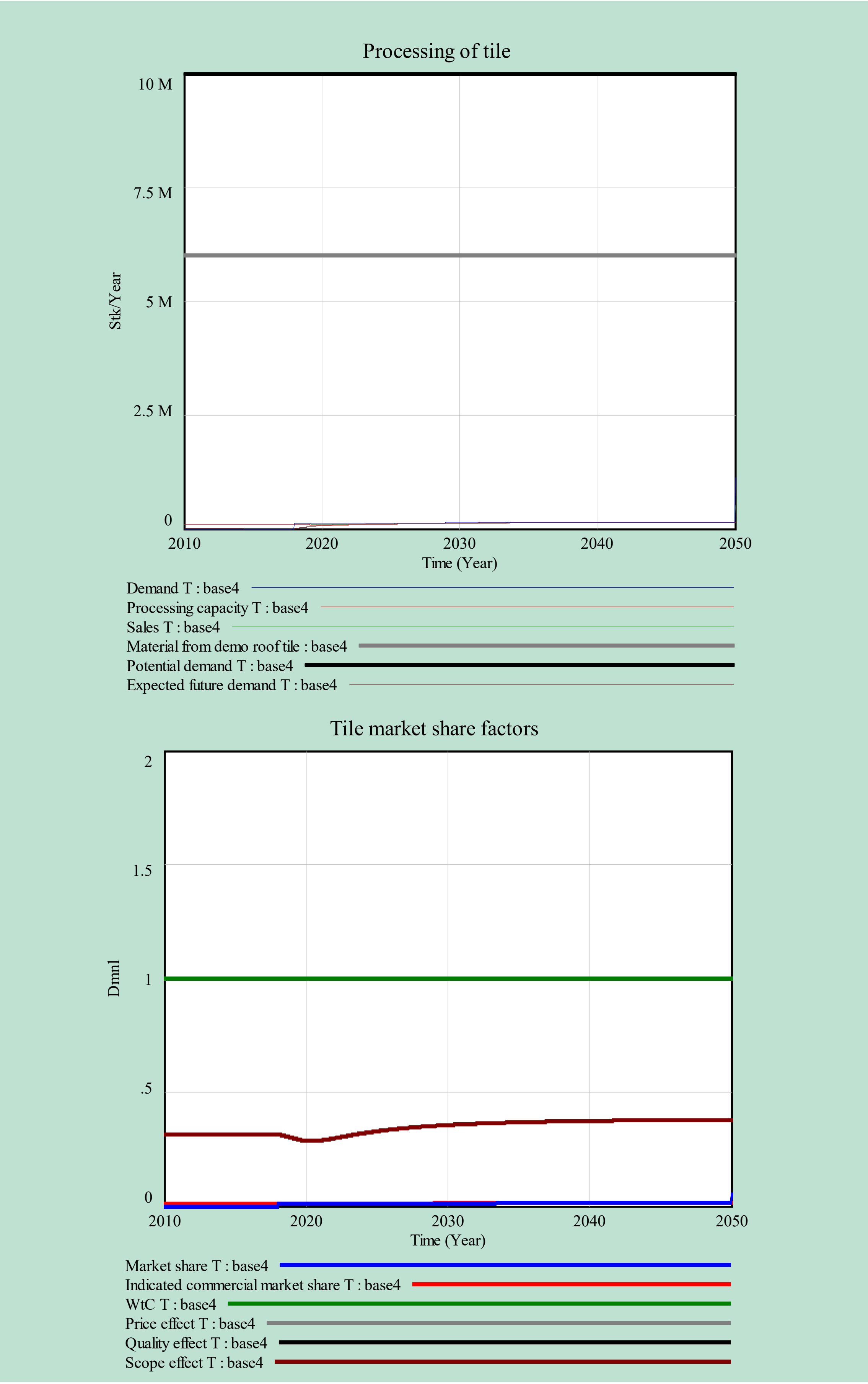

FIGURE 9. Tile market base run 4: As FIGURE 8 but with scope economy activated (ρ_T=0.5)

7.1.3 Wood market

For the wood market, we have chosen to exclude the awareness mechanism and instead focus only on the economic self-reinforcing feedbacks to illustrate how these can separately play a part. In the base run, the scale economy, the scope economy and the learning curve effects are all neutralized. Not surprisingly, the market therefore quickly materializes as shown in FIGURE 10.

On the other hand, if we introduce one of the feedbacks, say scale economies, by setting $\alpha = 0{,}5$ and $\pi = 0{,}5$, say, the result is once again a failure for the market to take off (see FIGURE 11). Note that now it is not lack of awareness but the inertia implied by scale economies that holds the market back.

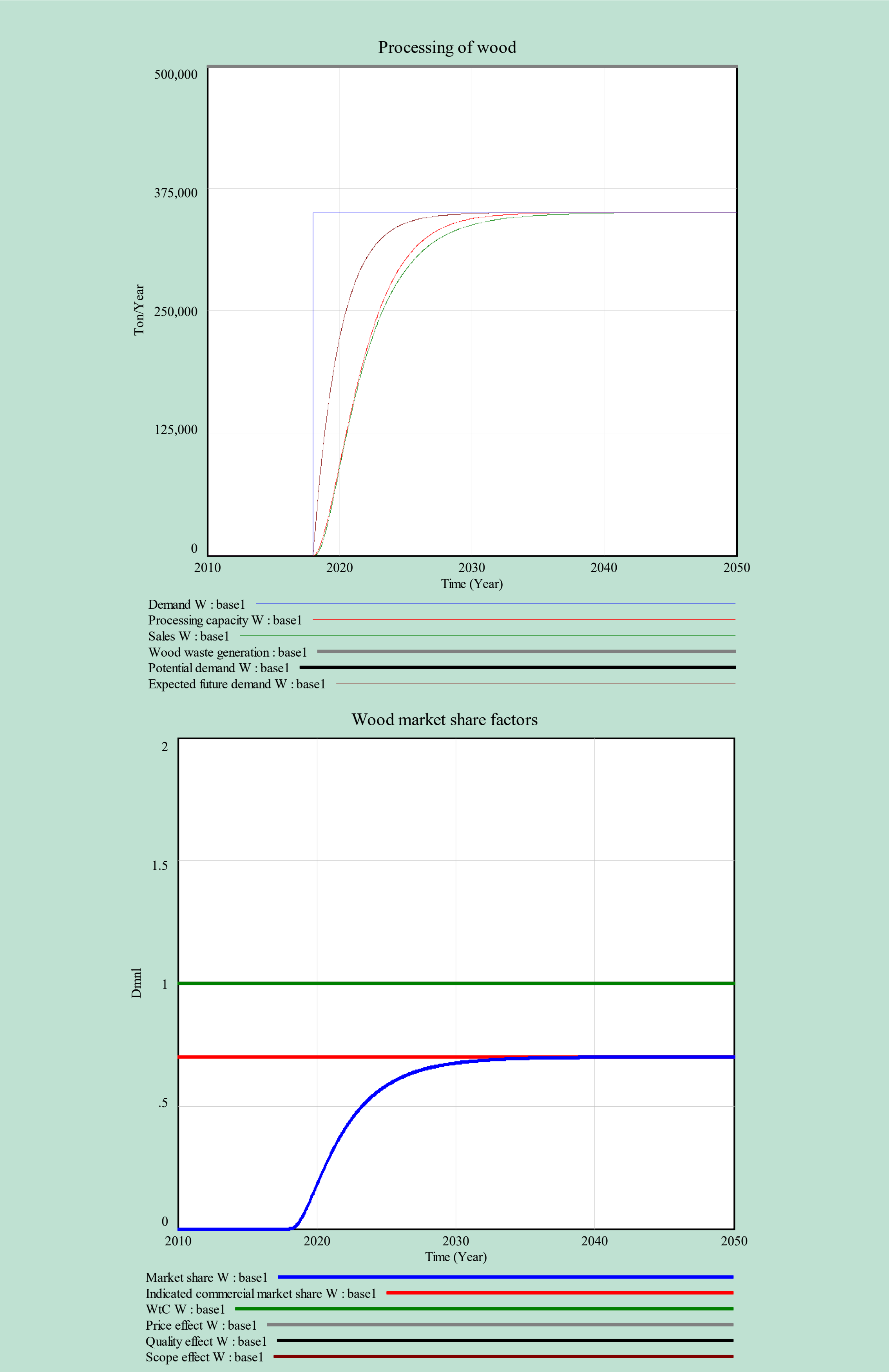

FIGURE 10. Wood market, base run: No policy initiatives to enhance secondary markets

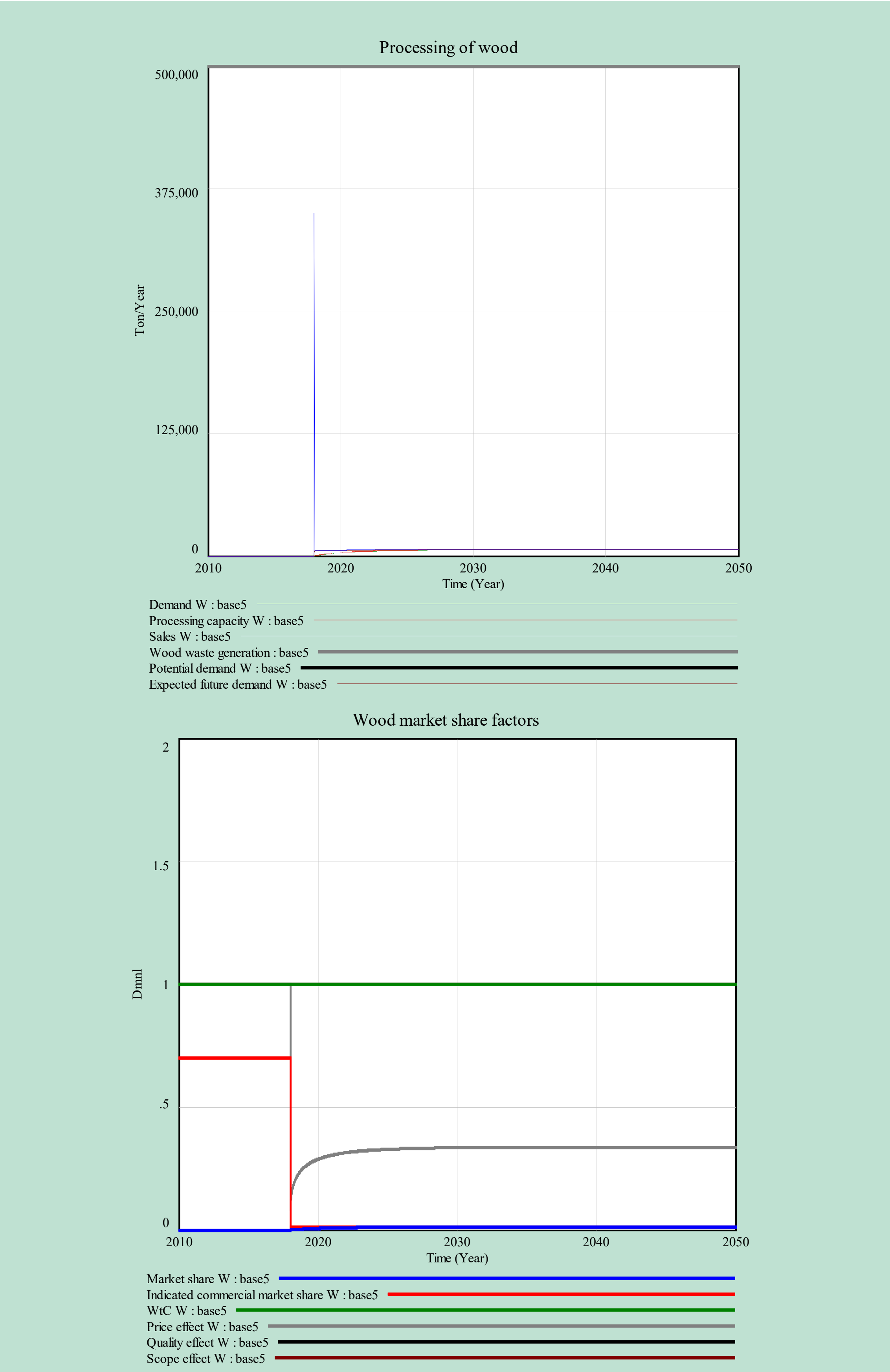

FIGURE 11. Wood market, base run 4: Activation of scale economy mechanism

7.1.4 Reference base case

Based on the results above, we have chosen the following set of parameter changes as our "problematic" reference case, where the three markets fail to take off. This will allow us to examine the impacts of the policies in the following.

$\rho_T = 0{,}5$	Strength of scope economy effect, tile market
$\pi_W = 0{,}5$	Price sensitivity, wood market
$\alpha_W = 0{,}5$	Strength of scale economy effect, wood market

The first two parameters, ρ and π, measure the percentage change in attractiveness from a one percent change in the size of the market and the product price, respectively. The third parameter α measures the percentage reduction in unit production cost with from a one percent increase in the scale of production. Evidently, one could choose many other combinations of parameter assumptions as a point of departure, but within the scope of this project, we cannot consider all of them. Nonetheless, we still consider the results of the policy analysis below interesting as a way of raising potential issues.

7.2 Policy no. 1: Certification, warranties, materials passports

We begin by considering the effect of this policy on market awareness. (This is only relevant for the concrete and tiles market in the model, since the effect has been taken out of the wood market. This does not mean that it would not be relevant in real life, however.) We introduce the effect of the initiative by assuming that the remaining gap in consideration (WtC) is reduced by 10 % each year for 5 years, starting in 2018. Moreover we assume that the strength of the word-of-mouth effect is doubled.

The result is shown in FIGURE 12 for the concrete market and FIGURE 13 for the tiles market. We see that the scheme has a strong effect on the concrete market, where a full transition has occurred within 10 years.[13] All in all, the policy seems successful.

[13] The market is now constrained by the supply of raw material from demolitions. While the demand for new aggregate is about 3 mio. tonnes, and demolished concrete is almost as much, only 20%, or about 0,5 mio. tonnes, is assumed to be suitable for RA processing.

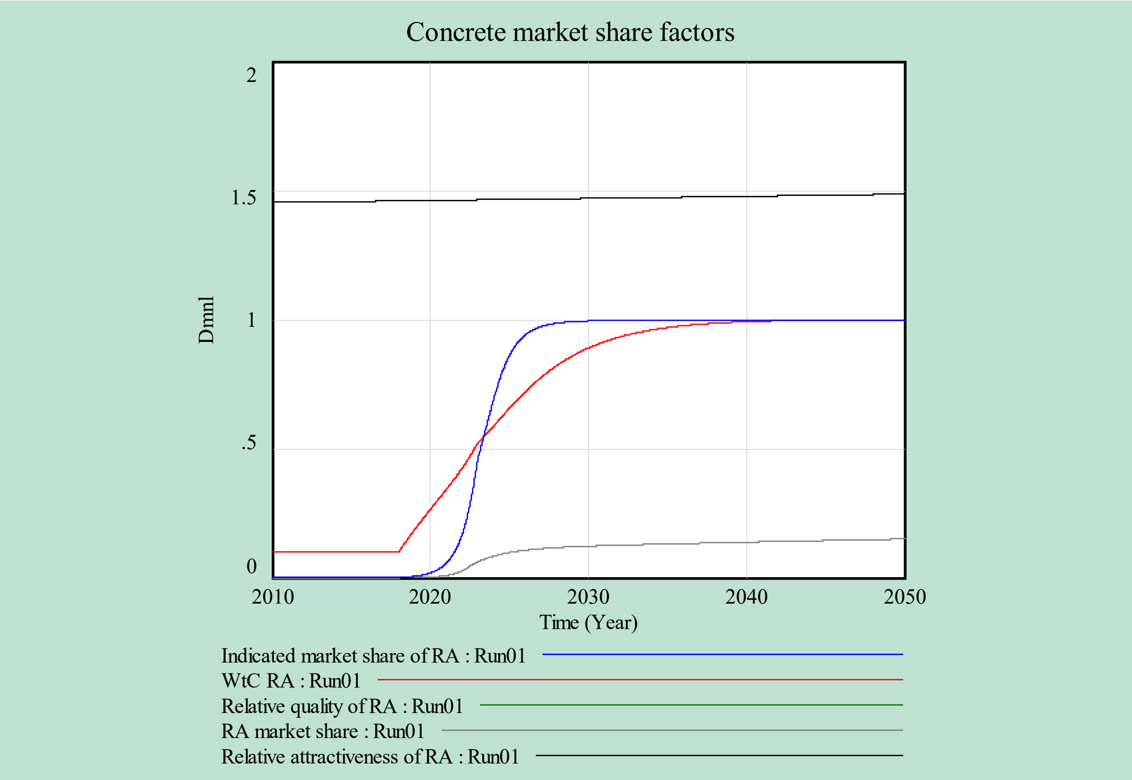

FIGURE 12. RA market, run 1: Effect of certification on market awareness

On the other hand, the same intervention in the wood market does not produced the desired effect (cf. FIGURE 13). Although the campaign does increase awareness from 10 % to 50 %, it is not enough to "get the snowball rolling", and the market fails to materialize. In other words, the powerful inertia in the tiles market from to the inventory requirements and the scope economy effect are enough to prevent transition.

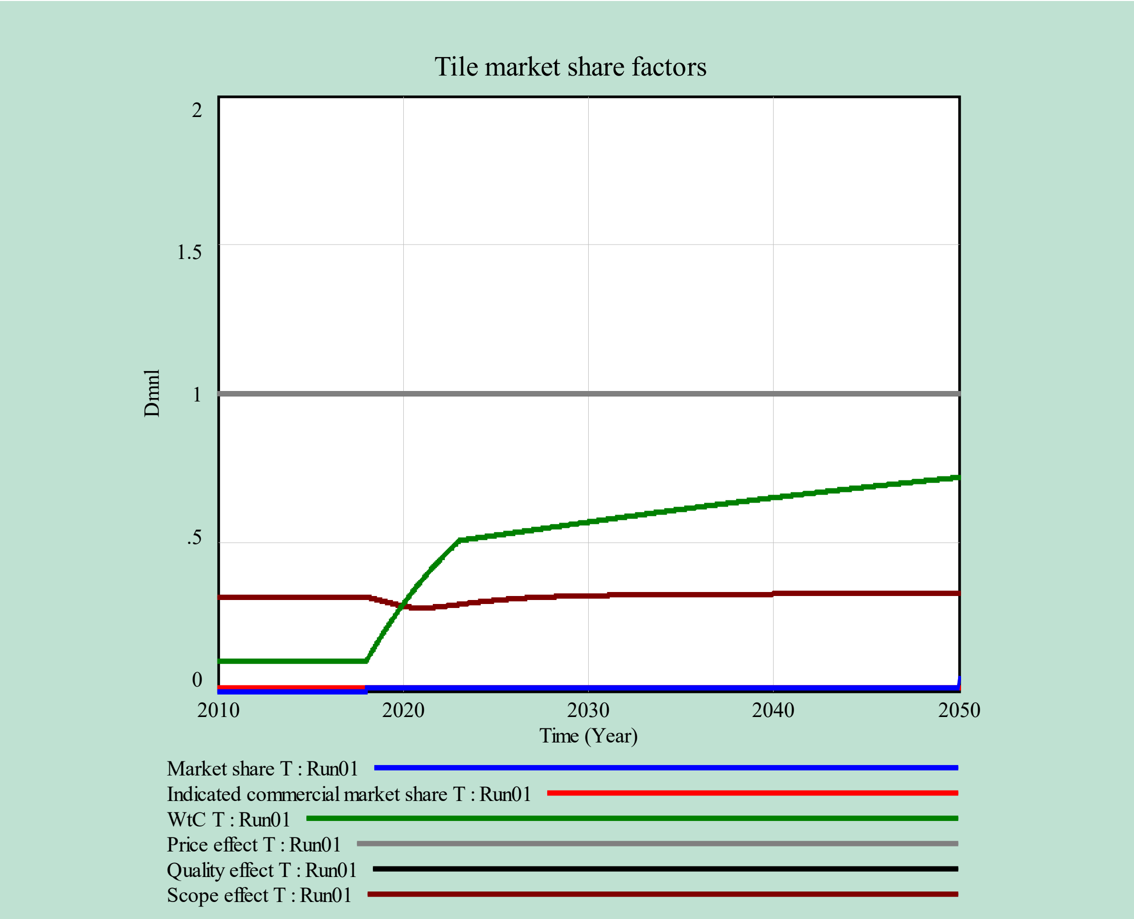

FIGURE 13. Tile market, run 1: Effect of certification on market awareness

Could the other effect of certification, raising average quality, by any chance make a difference? We test this question by assuming that the initiative makes the wood product twice as attractive, probably an optimistic assumption. We see in FIGURE 14 that a transition does occur around 2035, so the results are better, though hardly satisfactory.

The wood market, having no active WtC effect, can still be affected by the certification policy to the extent that it improves product quality. This is illustrated in FIGURE 15, where we have assumed that the certification is enough to lift quality by 50 % and we assume a market sensitivity of $\theta_W = 1$. The result is that there is a transition within 15 years. Here, the effect is clearly more dramatic than what we saw in the tiles market.

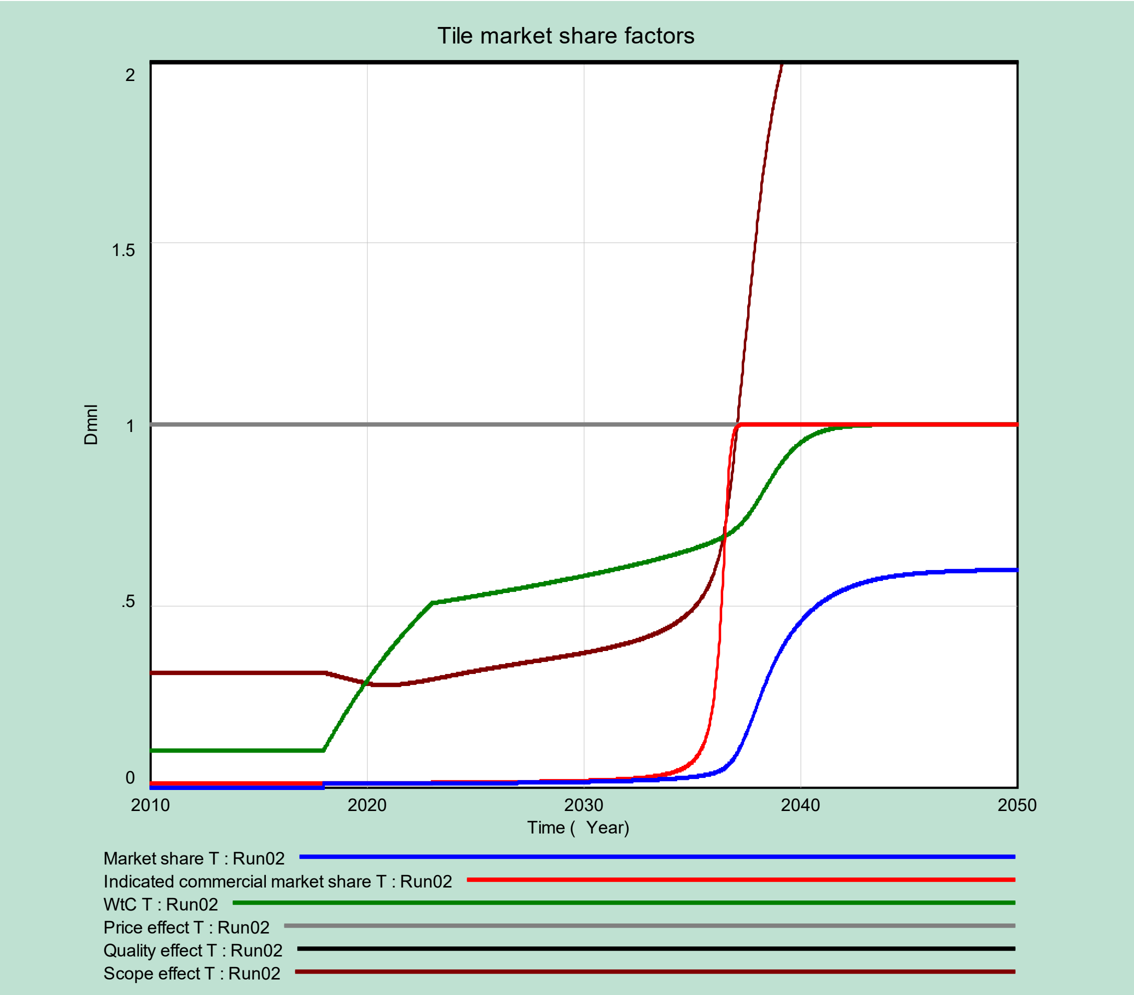

FIGURE 14. Tile market run 2: Adding an effect of certification on quality

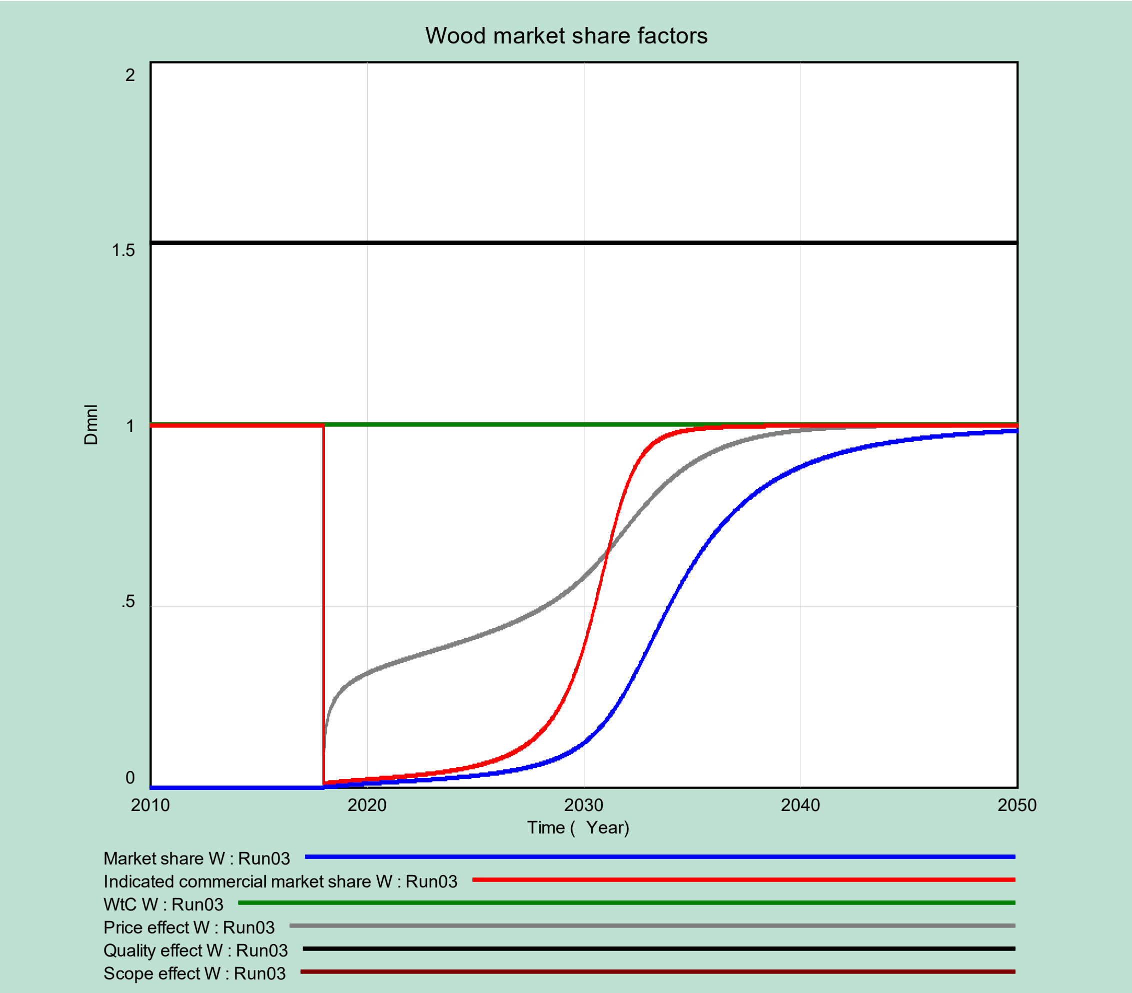

FIGURE 15. Wood market run 3: Effect of certification on quality tips the scales

7.3 Policy no. 2: Trading and matching platform

The trading platform in many ways acts in a similar fashion to the certification policy to enhance market awareness. In addition, however, it also has the potential of reducing both the required scale to obtain scope economies and the required inventory to assure security of supply. Since we have already tested the former effect in the first policy initiative above, we now focus on the second effect but retain the assumption that increased awareness amounts to a 10 % "marketing effect" for 5 years. We further assume that the reference scale for scope economy is cut in half from 1 mio. to 500.000 pieces per year. The result, shown in FIGURE 16 is that the transition is moved forward by a decade. The faster realization of scope economies can thus be a significant factor resulting from this policy.

On the other hand, if we only implement this, and do not address the quality issue, the results are disappointing, as seen in FIGURE 17. The result is that the market fails to take off.

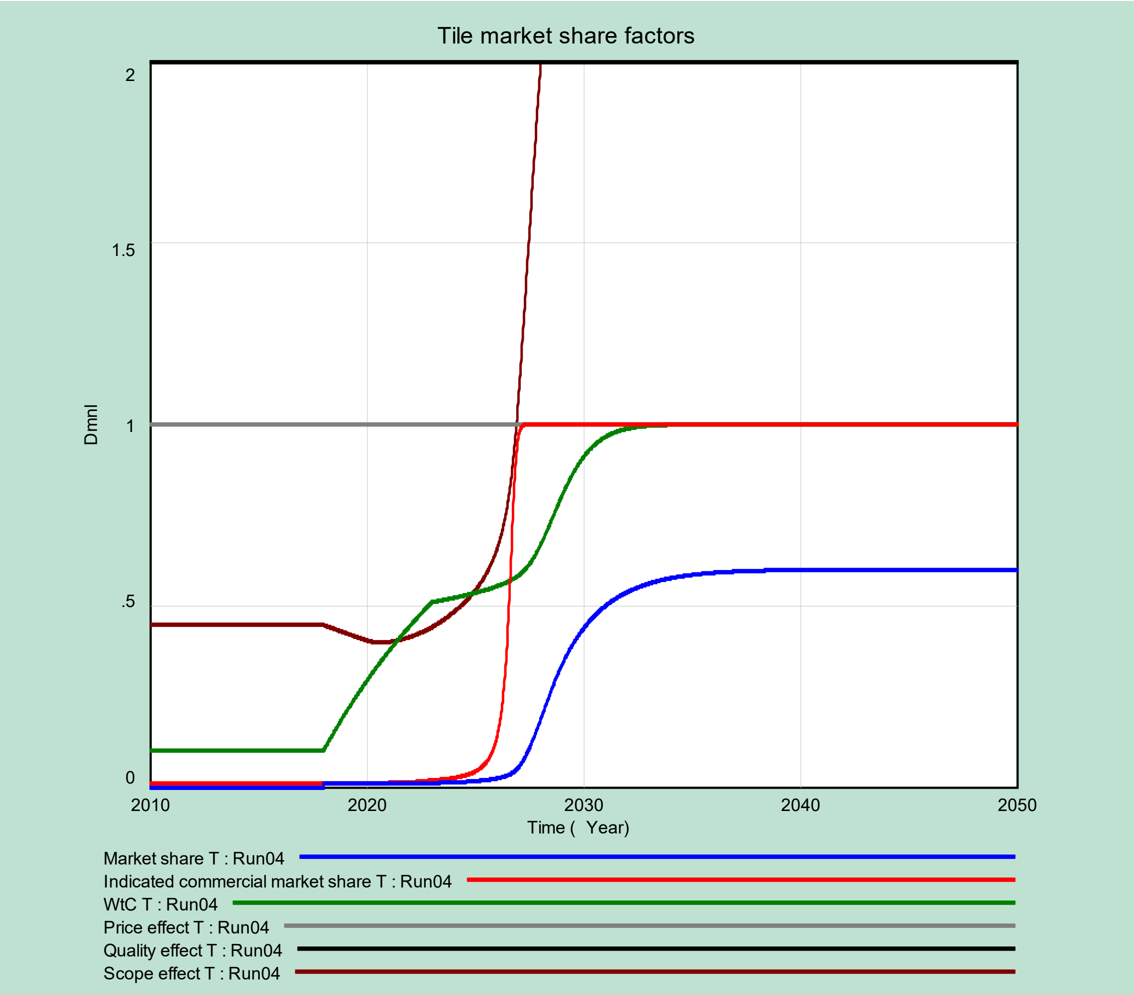

FIGURE 16. Tile market run 4: Effect of reduced reference scope capacity from trading platform

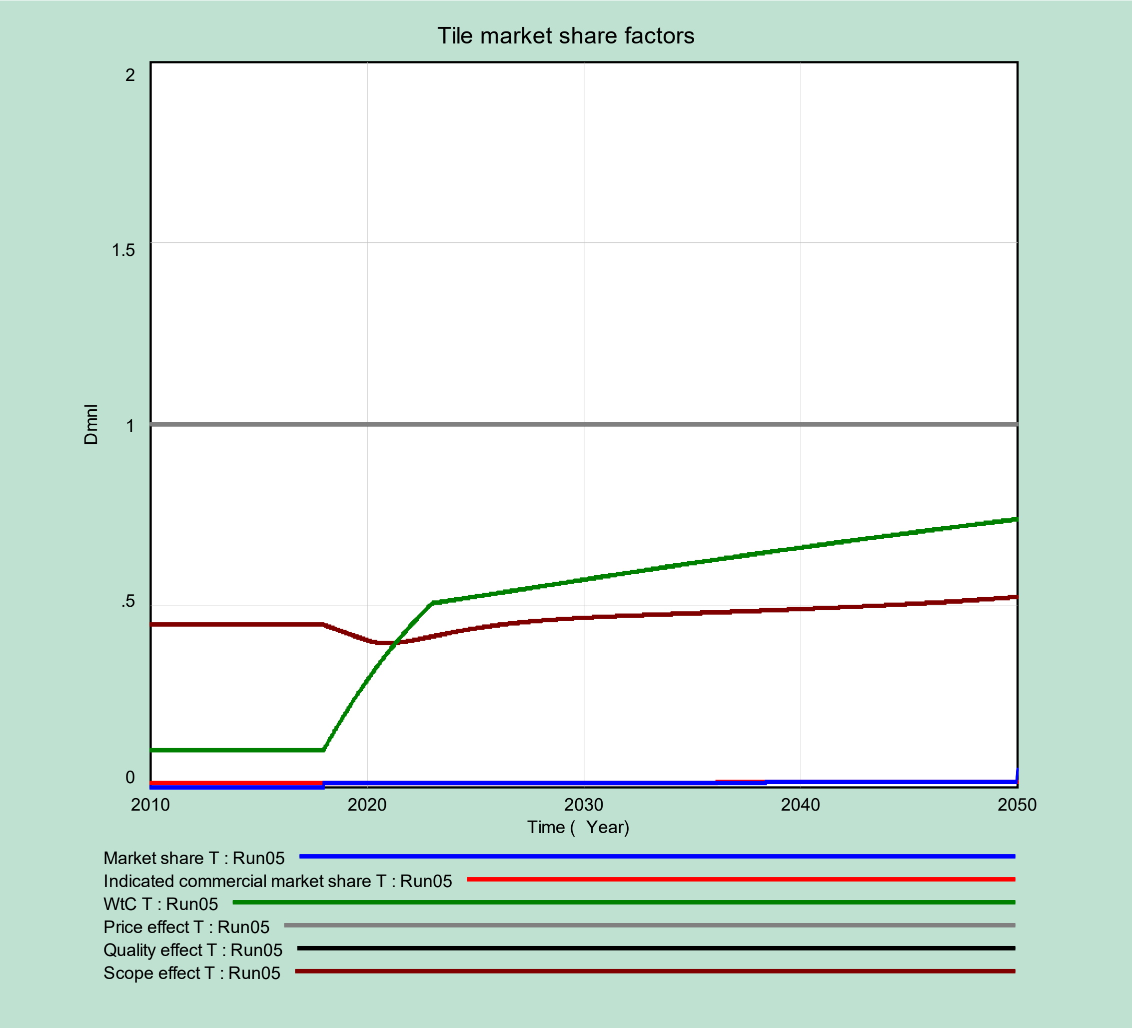

FIGURE 17. Tile market, run 5: Trading platform but no quality improvement

7.4 Policy no. 3: Value demonstration projects

As the value demonstration projects mostly work by affecting market awareness, which we have already considered above, there is no need for further simulations specific to this policy. Its effects can be inferred from the above.

7.5 Policy no. 4: Green public procurement (GPP)

We introduce GPP in the model by assuming that a certain fraction of total potential demand (10 %) is unresponsive to variations in the attractiveness parameters. We initiate this policy in the year 2020. The results are shown in FIGURE 18 for the RA market, in FIGURE 19 for the tiles market, and in FIGURE 20 for the wood market. In the former two, the policy is clearly successful: by driving up market share and awareness, the policy helps the positive feedback loops in the market system get activated, so that the market transitions on its own after about 15 years.

On the other hand, the policy does not appear successful in the wood market, where the awareness mechanism is not activated, and where the boost from GPP is insufficient to realize the positive feedbacks from economies of scale to effect a transition. The result is sharply different from the result of certification on quality seen in FIGURE 15.

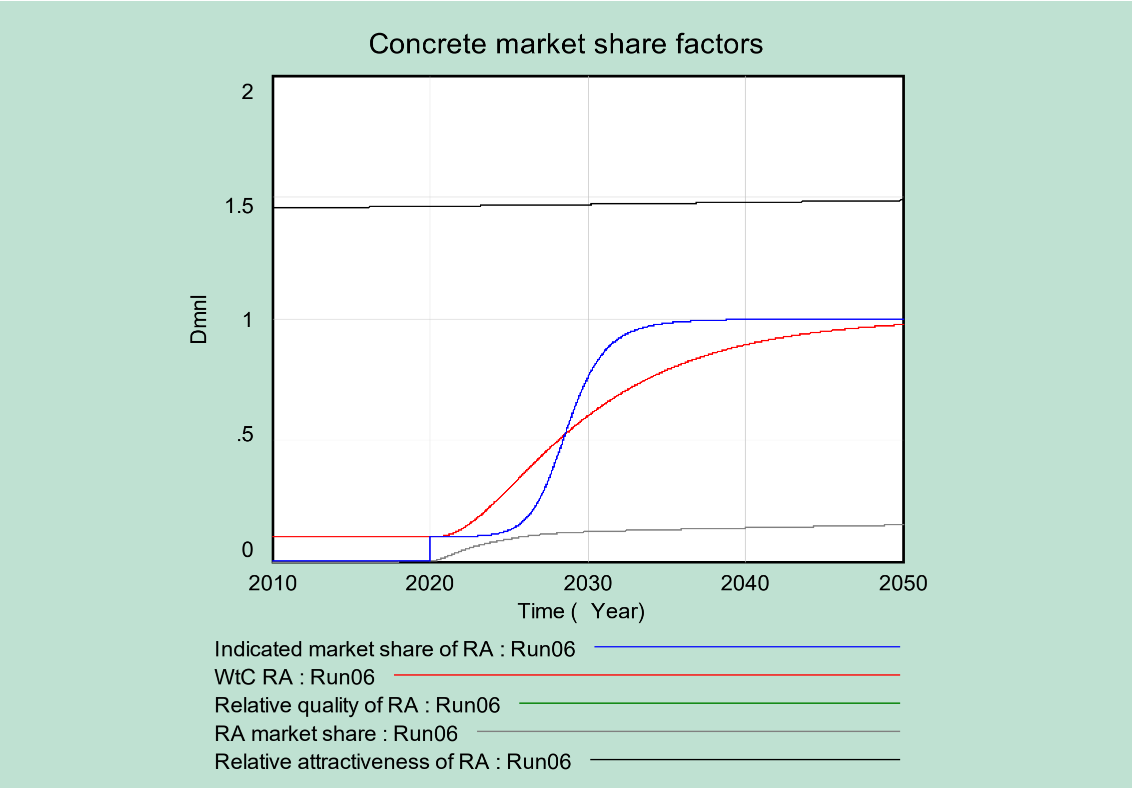

FIGURE 18. Concrete RA market, run 6: GPP policy

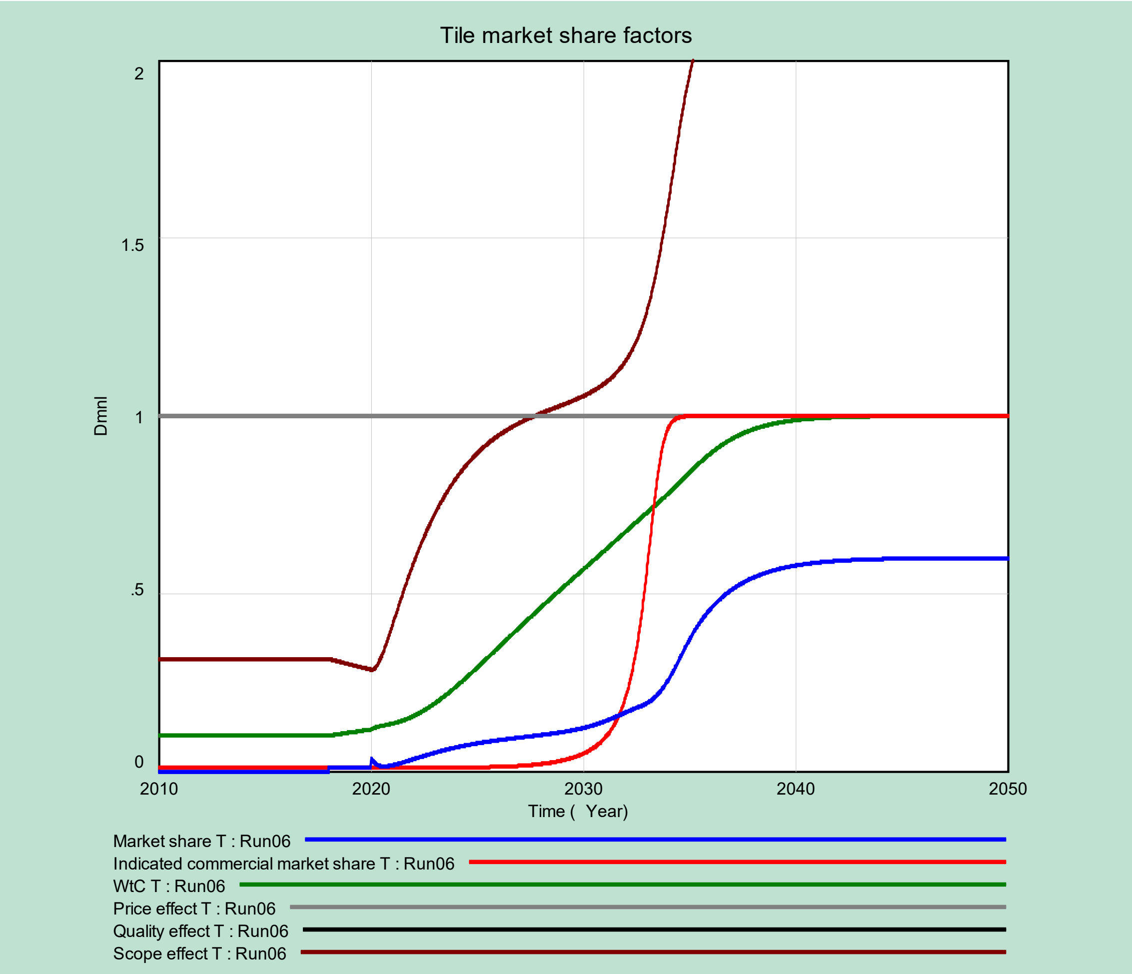

FIGURE 19. Tile market, run 6: GPP policy

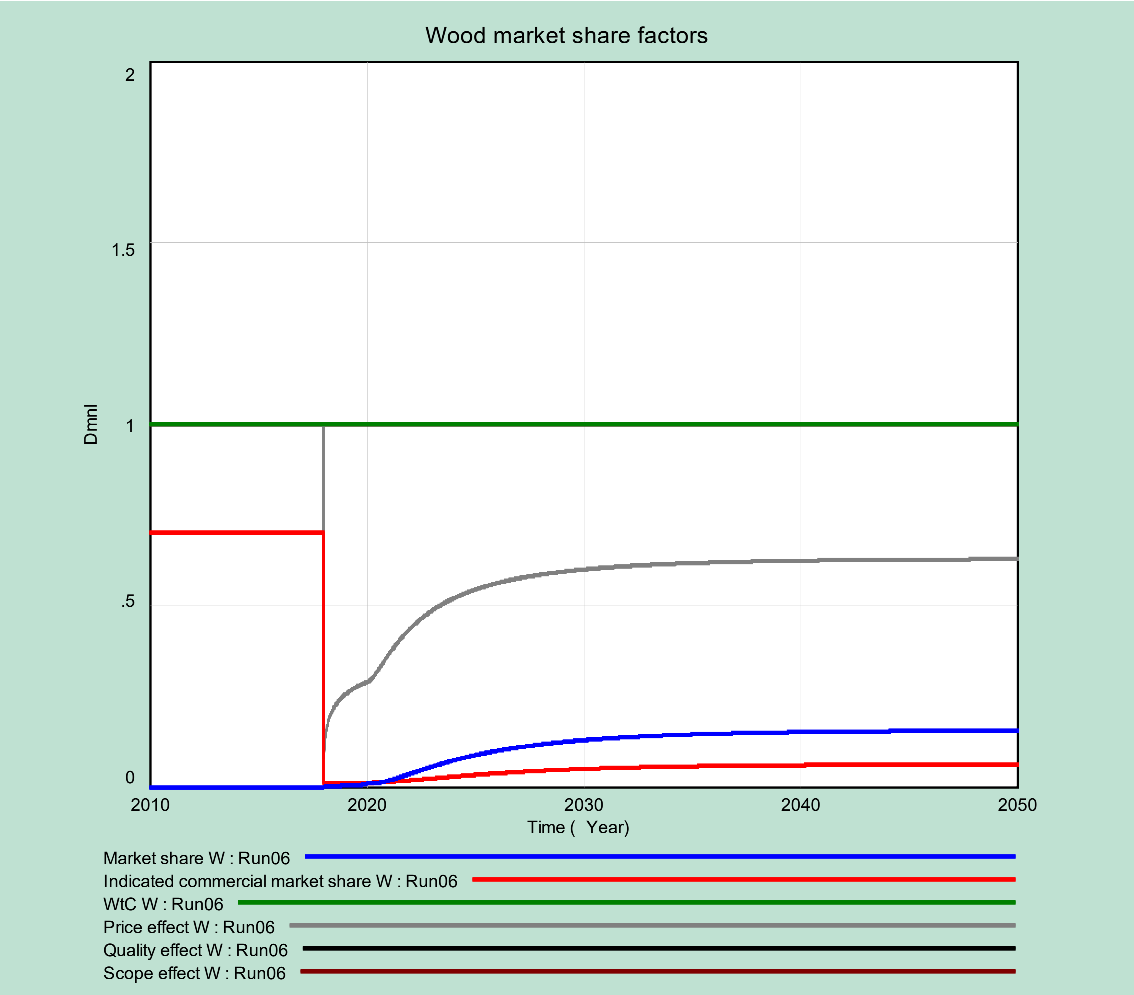

FIGURE 20. Wood market, run 6: GPP policy

8. Conclusions

8.1 Current status quo of C&DW markets in Denmark

The current C&DW management in Denmark is delivering a smooth market functioning and high recycling rates. The establishment of material markets dates back decades and the procedures and processes are well defined with clear roles for all stakeholders involved. All in all, it is safe to say that the current markets work well in the cases of concrete, wood and roof tile wastes. This can be further interpreted as the markets are stable, require no external support (e.g. subsidies) and fulfil state requirements such as recycling targets and removal of hazardous substances.

Given also the inherent conservatism in the building sector as a whole, the effective functioning of the existing markets leads to inertia towards new initiatives and approaches as well as towards new secondary products entering the market.

Denmark has a leading role in managing C&DW in a European context in terms of recycled quantities. The market model followed in Denmark is also present in a some other EU countries with smaller or larger differences. However, according to our desktop research, there are no C&DW markets established in other EU countries that can be characterized as more effective than the Danish one. Examples of successful alternatives to what happens in DK exist, but they so far only capture a small market segment or address niche markets.

8.2 Future market considerations

The model scenarios do confirm that all four of the suggested initiatives (**Certification schemes, product warranties, and “material passports”, matching and market-making trading platform, demonstration projects with focus on costs and benefits**, g**reen public procurement**) have the ability to activate the markets, at least under the assumptions made in the model. The initiatives operate on different points in the system. The demonstration projects, the market matching platform, and the certification schemes all serve to improve the information level to buyers and/or mitigate the risk associated with limited information. In the case of recycled concrete aggregate, which is already competitive in many ways with virgin material, this is enough to afford a transition of the market to overcome the initial inertia (WtC). In the case of roof tiles this may in itself not be enough to create a change.

However, the market matching initiative also has the ability to improve the scope economy of suppliers by reducing the required volume and stock on hand to provide a sufficient selection or variety. Whether this is enough to create a transition is an open question. With the parameters used in the model, the results were very sensitive to the reduction in required scope.[14] A relatively small difference would be enough to postpone the transition by a decade, or even prevent it altogether.

Green public procurement looks like a fairly effective way to bring about a transition. By providing a minimum volume of demand for the secondary materials, it allows enough momentum to let the market system activate the positive feedback loops in the market system, leading to a transition. Here, the assumption has been that 10 % of the market is subject to GPP rules, which may be a bit optimistic. But at least it shows in principle how the policy would work.

[14] The “required scope” is a measure of how large the market must be in order for there to be a sufficient selection of products available to make them relevant and attractive to the typical buyer. As discussed in section 7.3, a trading platform increases the effective selection and range of products a buyer can access for a given size of the market. In this manner, the market can achieve economies of scope at an earlier (smaller) market size than would otherwise be the case, hence effectively reducing the “required scope”.

One thing to notice from all the scenario simulations is that transition takes time. On average, the typical market transition takes about 15-20 years in the model. This is due to the large inertial factors in the system, both in the build-up of processing capacity for handling secondary materials, and not least for the build-up of sufficient market learning and changes in buyer behavior (attitudes). In light of other historical processes of transition, however, such a time horizon should not be surprising. But it does highlight the fact that policy makers may have to exhibit some degree of patience to allow the effects of the policies to play themselves out in the market system.

The market for recycled wood is probably the most uncertain, given the scarcity of data on economic drivers, scale and scope economies, etc. Pragmatically, since wood constitutes
a relatively small part of the total waste flows and since the re-use of wood materials seems more dependent upon development of new products and processes, such as structural composite lumber, it is probably also relatively less important to focus on. Indeed, from an environmental standpoint, it may more sense to continue the current processing of wood into particle board and other simple products and then encourage the use of virgin wood for building material as a way to sequester carbon in the built environment.

At last, a word of caution: The simulations are all based on educated guesses of many parameters. A full analysis would require more sensitivity analysis, e.g. through Monte Carlo simulation testing of parameter ranges. However, given the short time horizon of this project, such an analysis was not possible. Moreover, regardless of the accuracy or formal validity of the results, the model does serve to raise some issues for further discussion among industry participants and policy maker, such as:

- the current rigidness of the market for secondary construction materials
- the need for higher quality applications for recycling or re-use
- the possibilities for retaining the quality of construction materials once these become waste
- the ideas for improving the market conditions around the use of secondary construction materials
- time scale issues for improvements to become effective
- proposals on how to best change stakeholders' willingness to consider construction materials' alternatives

8.3 The way forward for the modelling output

The work undertaken in this project should be viewed in the context of the partnership for sustainable construction and waste prevention. Therefore, the conclusions of this work will support the stated objectives of the partnership (see chapter 1.1).

The main output of this project is the development of a customized, economic simulation model that is able to produce results from changes in market conditions on the functioning of the secondary markets accommodating concrete, roof tiles and wood wastes from the construction industry. The model is a first attempt to understand how these markets respond to disturbances or disruptions in terms of new products' market shares and time scales for a change to become effective. The model also describes the conditions for these markets to become more effective in accepting new, innovative products from the processing of construction and demolition waste. This new development can be used by the partnership for diffusing specific knowledge to its members and stakeholders in the wider construction industry. The knowledge diffusion can be organized around workshops, seminars, etc.

However, the model is in a way still under development. Further validation is needed in order to increase further the model credibility and its ability to produce meaningful results. This can be done for example, by applying the model to other materials, by modelling other initiatives or by testing the model to specific case studies.

The model ownership lies with the commissioners of this project, namely the partnership and the Danish EPA. It is therefore freely available to a wide range of stakeholders such as the building agency (Byggestyrelsen), the knowledge centre for management and recycling of construction and demolition waste (VHGB), the Danish building research institute (SBI) etc.

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Appendix 1. Detailed model description

This appendix provides a detailed description of the simulation model used for the scenario calculations. Appendix 2 lists the detailed equations of the model and Appendix 3 lists the parameter changes used for each of the simulations included in the main report. The model was coded in the VENSIM software (version DSS 7.2, available from Ventana Systems, Inc., http://www.ventanasystems.com/software/). The model file, BM008.mdl, as well as the specification of parameter changes to perform each of the included simulations, *.cin, the resulting simulation data, *.vdf, and a Microsoft Excel file of the historical data, HISTORY.xlsx, are all available for download at https://www.dropbox.com/sh/3pd6xpvtvujkdy5/AAAxaoX5KEVH3j2ftQihCrEqa?dl=0).

I.1 Modeling approach and purpose

The market simulation model is based on a methodology called system dynamics, a quantitative method that uses dynamic models to simulate socio-economic systems.[15] One of the challenges of modelling markets that do not yet exist is that there is no history on which to base future projections. Hence, any analysis will contain a great deal of uncertainty about future demand, supply, prices and costs. Moreover, there may be factors affecting market performance that may not be available ever in a statistical form. For instance, conservative attitudes or beliefs of decision makers, or general skepticism towards new products, may be an important influence on the emergence of the market, yet may not be easy to measure or record. One is left, essentially, with having to make educated guesses about such factors.

The system dynamics method is designed to deal with this situation from the point of view that even though a quantitative model may be based on limited data, it is still better than the alternative. The main emphasis of the method is to afford a qualitative understanding of possible important issues that can arise in the future. Given the assumptions entered into the model, the exercise affords the ability to trace out the logical implications of these assumptions in a consistent manner. Moreover, there is a great deal of emphasis on the qualitative explanation of WHY certain outcomes appear, as opposed to the numerical details of WHAT they are.

One may be sceptical of the ability of such modelling to provide meaningful results: If a large number of parameters are based on guesswork or ad-hoc assumptions, how can you have any confidence in the outcomes predicted by the model? However, the experience from the field is that since you are dealing with highly nonlinear dynamical systems, the outcomes are hard to anticipate in advance, and since the system contains many compensating feedback mechanisms that counteract specific policies, it is often the case that the results are surprisingly insensitive to variations in the input assumptions, particularly when the main emphasis is on qualitative substantial differences rather than numerical accuracy.

The project involved constructing a simulation model of the future markets for the three waste fractions, concrete, wood and roof tiles. The elements that were thought to be of particular importance were

6. Possible **learning-curve effects** on costs, allowing unit cost of recycled and re-used materials to decline over time with increasing industry experience.
7. **Scale economies**, where larger markets for distribution, storage, classification, and marketing would lower the average cost of recycled or re-used materials.
8. **Scope economies**, where a wider range of different products would afford a better match between the requirements of a specific construction project and the re-used materials available on the market. This is thought to be particularly important for the roof tile and wood market, since both of these materials

[15] For a comprehensive description of the system dynamics method, see Sterman, J.D. (2000) Business Dynamics: Systems Thinking and Modelling for a Complex World, McGraw-Hill.

would presumably retain much of their original form at the time of demolition. For the concrete market, where the waste product is crushed and mixed into a homogenous product, this is likely to be of less significance.

9. **Market learning and adoption**: A crucial factor in any adoption of new products and processes is the customers' awareness or **willingness to consider** the new alternative products. Given the importance of quality and timeliness of delivery in construction projects and the substantial financial risks involved of delays, poor quality, or environmental issues with problematic substances found in materials, it is not surprising that buyers may be sceptical of any new material source. In addition, the construction industry is more characterised by competition in cost, quality and timing than by product or process innovation, leading naturally to a more conservative attitude among its actors.
10. **Availability and security of supply**. Given that timeliness plays a crucial role in construction projects, the security of getting on-time deliveries is bound to play a crucial role in the performance of the market. Therefore, having sufficient supplies on stock will be a key success factor.

All of the factors mentioned above will in effect constitute a set of self-reinforcing mechanisms for the evolution of the market, as illustrated in FIGURE 21. Lower cost from scale economies or learning curve effects, increased scope economies, increased market acceptance and security of supply through large-scale deployment and variety in goods supplies, all of these effects are in turn dependent upon a sufficient market volume: the greater the market size, the more these forces will work to improve the quality and attractiveness of the product, providing the basis for further market growth. Hence, much of the purpose of the modelling has been to uncover these mechanisms and how policy measure may affect them.

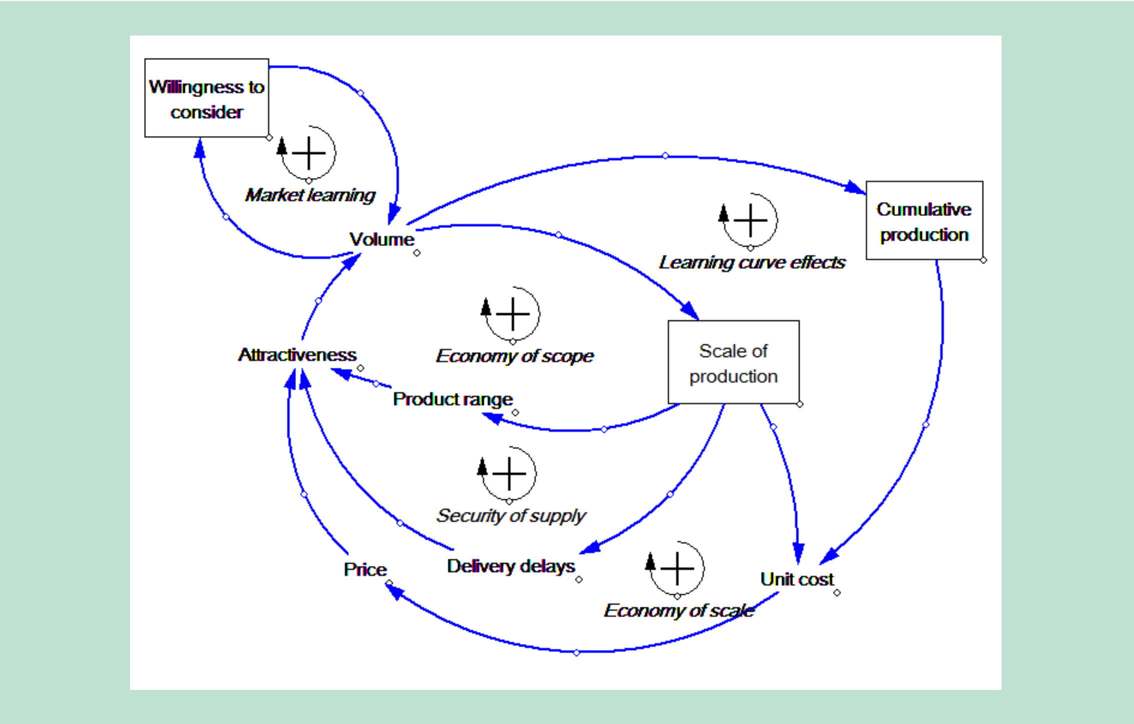


FIGURE 21. Positive (self-reinforcing) feedback effects driving market evolution

The current state of the model is open-ended, reflecting the exploratory nature of the modelling project. The intention is that the model can be further modified and developed for follow-up projects. In particular, given the fast and interactive nature of the simulation software, it is possible to do so "live" in project meetings with the users of the results. Indeed, this reflects the main purpose of the modelling, to stimulate understanding and discussion.

I. 2 Mass flow modelling

In the following, we describe the model's representation of the physical flows of the three waste fractions. The model keeps track of the physical flows of the materials from construction to demolition to re-use or recycling or other ways of disposal. The three segments are modelled somewhat differently. In all cases, the model attempts to track how much material is embedded in new building structures at the time of construction.

Concrete

FIGURE 22 shows an overview of the material flows of concrete as they are represented in the model.

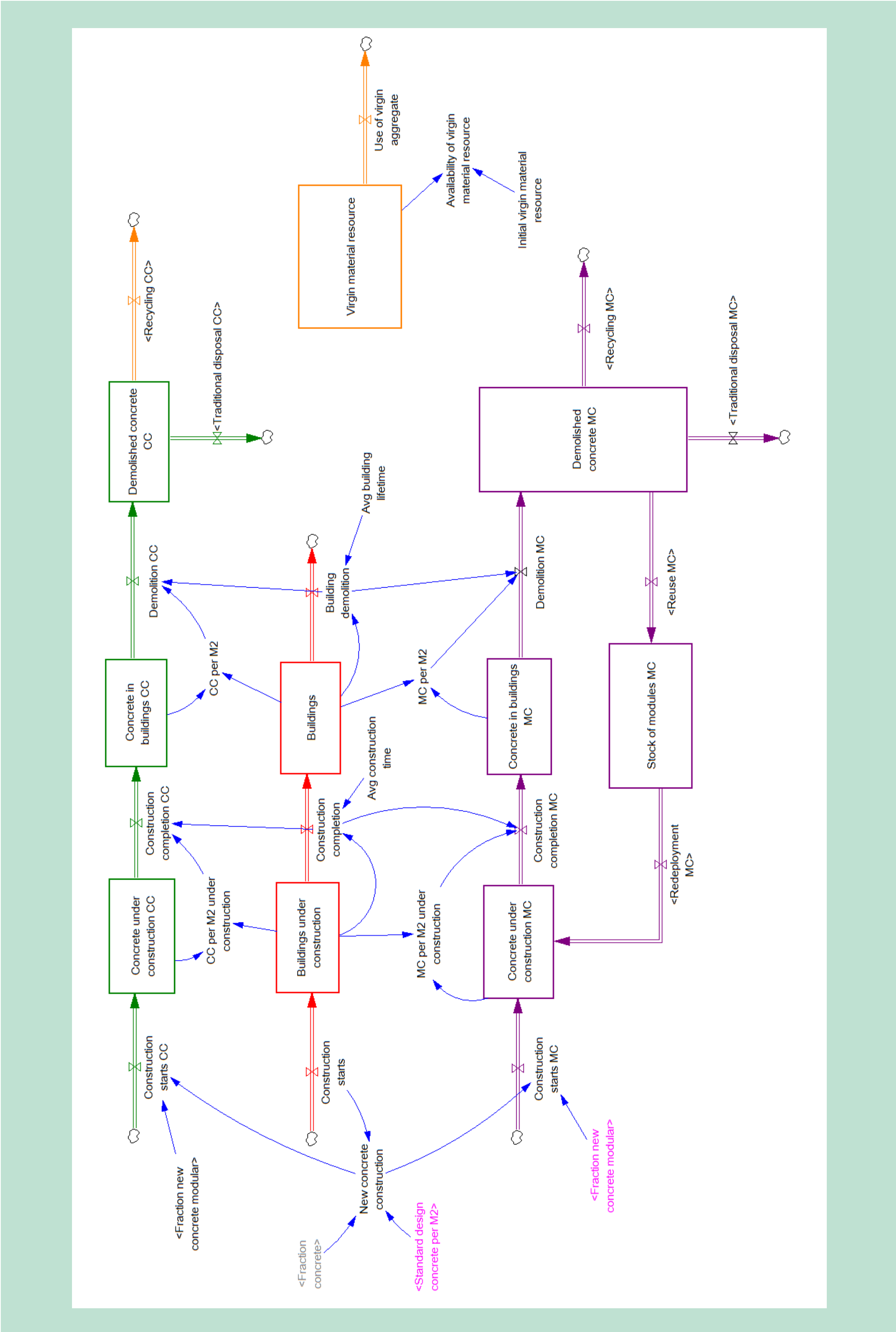
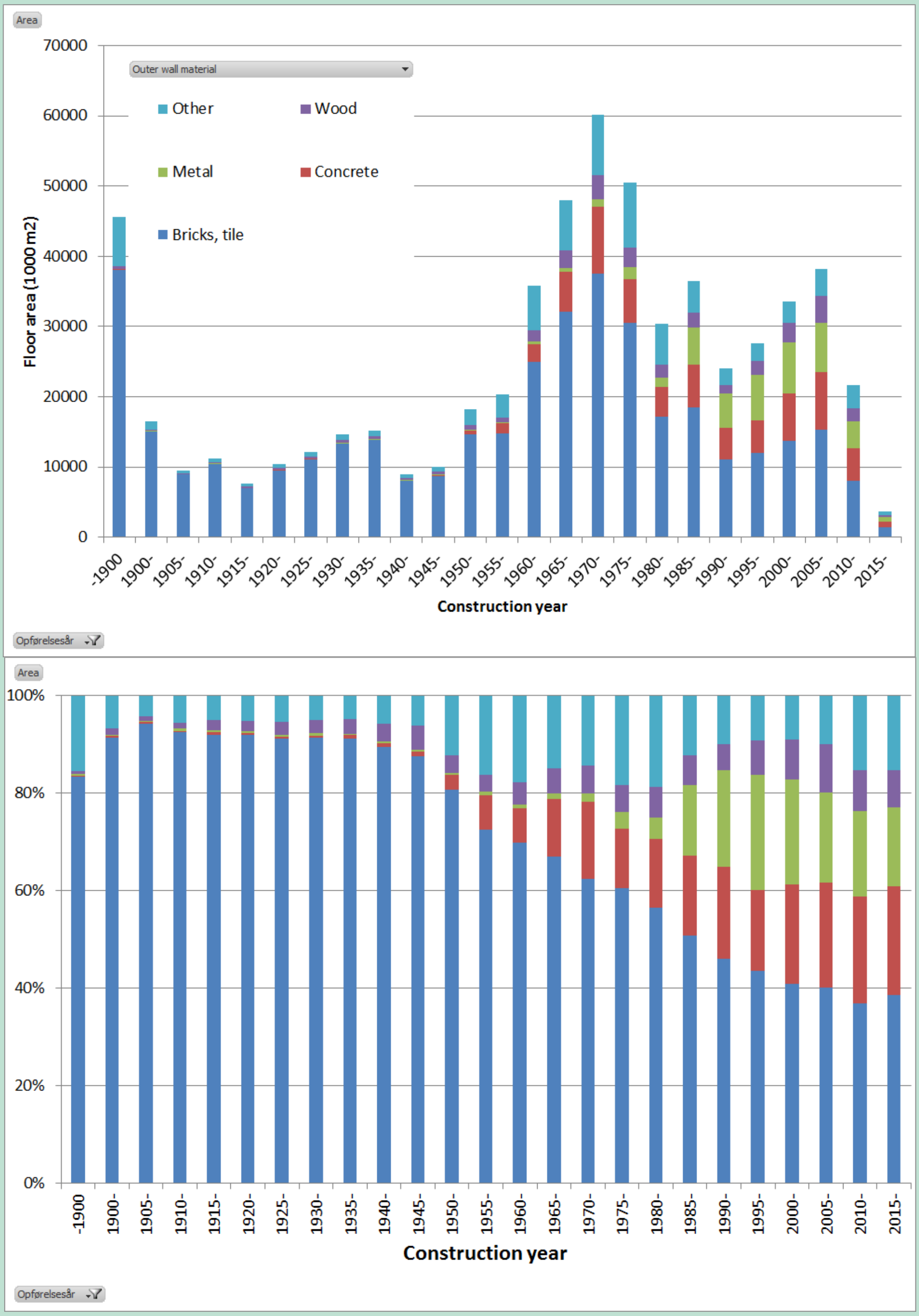


FIGURE 22. Material flows of concrete in the model

The model keeps track of the concrete that is embedded in built structures (red). There is a distinction between buildings of conventional design and buildings (green) that are explicitly designed a modular fashion for disassembly (purple). Concrete waste is either disposed of in traditional fashion (e.g. for road sub-surface or filler, as is the case today), or it is processed and recycled into aggregate for new concrete (orange).

The share of building structures with concrete as their main exterior wall element has changed quite significantly over the years. We are fortunate to have fairly detailed data on this from the BBR registry of Danish buildings. The slow turnover of the built environment (red)represents a significant source of inertia when going from traditional buildings to buildings designed for disassembly and re-use (modular concrete). A change in the split between modular and conventional new concrete structures (purple vs. green) will therefore take many decades to manifest itself as a change in the split between the overall stocks of the two structures.

FIGURE 23 shows construction of new buildings classified by type of exterior material, measured by dwelling or office area (a) and by fraction of total area (b). This information is important because it gives an indication of how much secondary material may become available as the structures are demolished to make room for new construction in the future. What is immediately evident from the figure is that concrete exteriors did not start to become prevalent until the 1960's. Before that, brick was the predominant material. However, since the 1990's, concrete has constituted about 20% of new buildings (see FIGURE 23b). This information can prove to be very useful for future market predictions, if one can get a reasonable impression of the relationship between the age of a building and when it is likely to be demolished for reconstruction or refurbishment.



Source: Statistics Denmark, Table BYGB60

FIGURE 23. New structures, by outer material and year of construction, in m2 of dwelling area (a) and share of total dwelling area (b)

In the model all buildings are assumed to have an average lifetime of about 85 years, but without considering an explicit "aging chain" of the buildings. (This assumption is easy to relax but introduces further complexity in the model, which was deemed unnecessary in this initial study.) The model uses the historical data for the composition building exterior materials. Under this assumption, the result is a gradually increasing supply of concrete from demolition, as these buildings built in the 1960's and onwards become ripe for demolition. This is illustrated in FIGURE 24.

A fair criticism of the current version of the model would be that demolition, rather than just being a certain fraction of the existing buildings torn down each year, would be driven by new construction, since a fully built out country like Denmark does not have much virgin land on which to construct new buildings. This would probably imply more fluctuation in demolition, as the construction sector is highly sensitive to business cycle fluctuations. In this initial study, however, we have chosen to ignore this aspect.

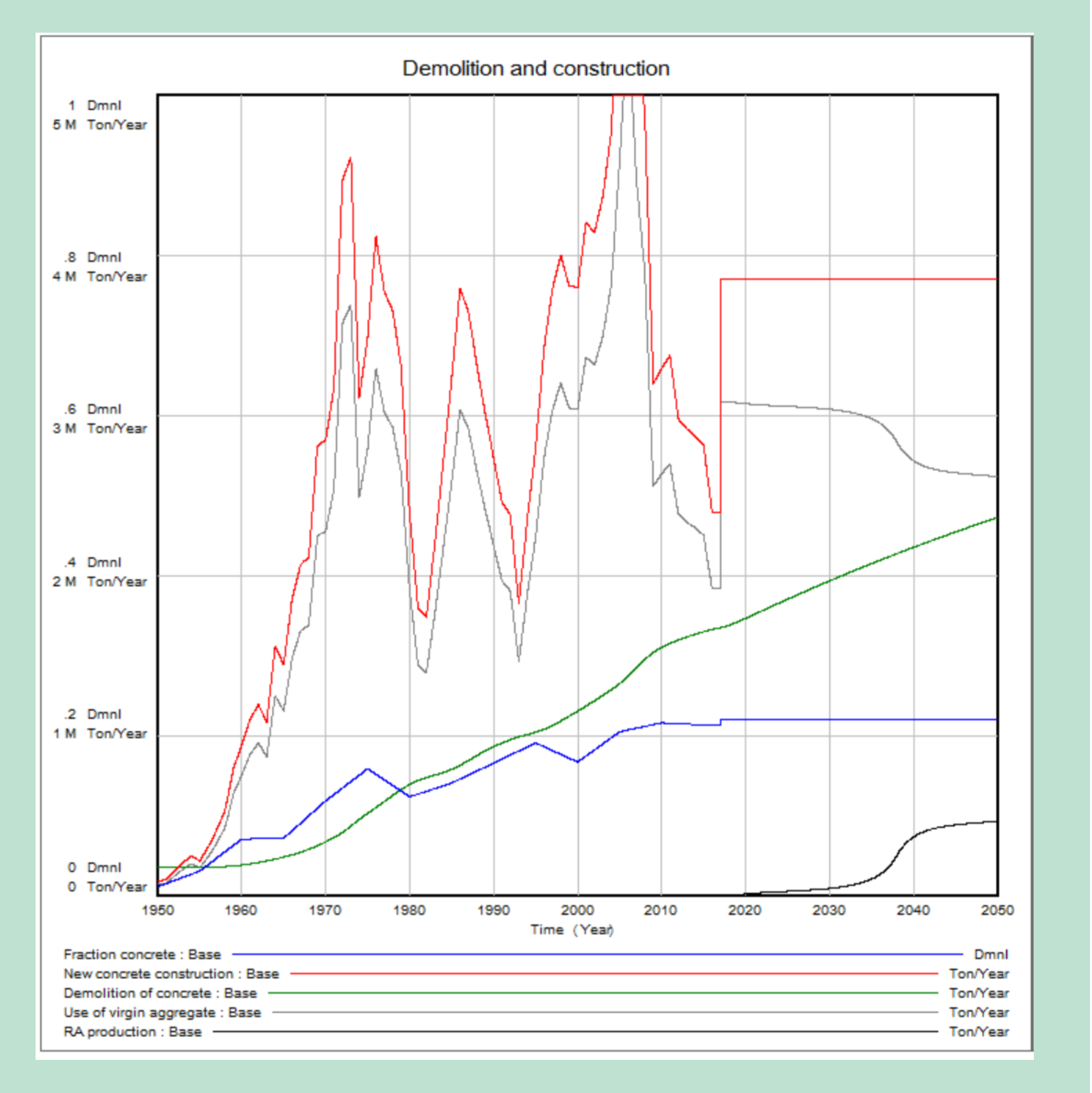


FIGURE 24. Simulated new construction, demolition and supply of demolished concrete

Once demolished, the concrete is assumed to follow one of three possible paths (see FIGURE 22). Either it is disposed of in the "traditional" matter, by crushing it and converting it to either filler material or sub-base for road surfaces etc. (the green "Traditional disposal CC"). Alternatively, the concrete can be crushed and processed and recycled as aggregate for new concrete (the orange "Recycling CC").

Finally, for future reference we also consider concrete that could be re-used as complete pre-fab elements in new construction ("Reuse MC"). This pathway presumes that the building has been designed and constructed from the outset to be dismantled and re-used in this manner. At present, there are virtually no such buildings in the system. However, we considered it relevant to include the possibility in the model for this option, particularly in light of some of the new design paradigms emerging in the industry, where buildings are constructed for shorter lifetimes but at the same time for easy disassembly and re-use. We do not include any explicit analysis of this option but retain it as an option for future analysis, particularly since the environmental gains from re-use of modular concrete could be very substantial. The new buildings designed for disassembly and the re-use of concrete elements in this system are shown by the purple stocks and flows in FIGURE 22, Note that some parts of the modular concrete are not re-used in this manner but are instead crushed and used in similar fashion to the non-modular concrete in the green part of the diagram.

The model also keeps track of the amount of virgin material (gravel and sand) extracted for aggregate in producing new concrete (the orange “Virgin material resource” in FIGURE 22). Over time, the use of this non-renewable resource may become a significant factor, as prices may rise over time with the increasing scarcity of virgin material.

Roof tiles

In the case of roof tiles, there is also a supply of new waste material determined by the demolition of old buildings, as seen in FIGURE 25. Unfortunately, compared to concrete, as mentioned in the main report, there is little information on how many roof tiles are embedded in the existing structures, how it has varied over time, or even on the total amounts of waste generated each year, except an aggregate estimate of bricks, roof tiles and ceramics.

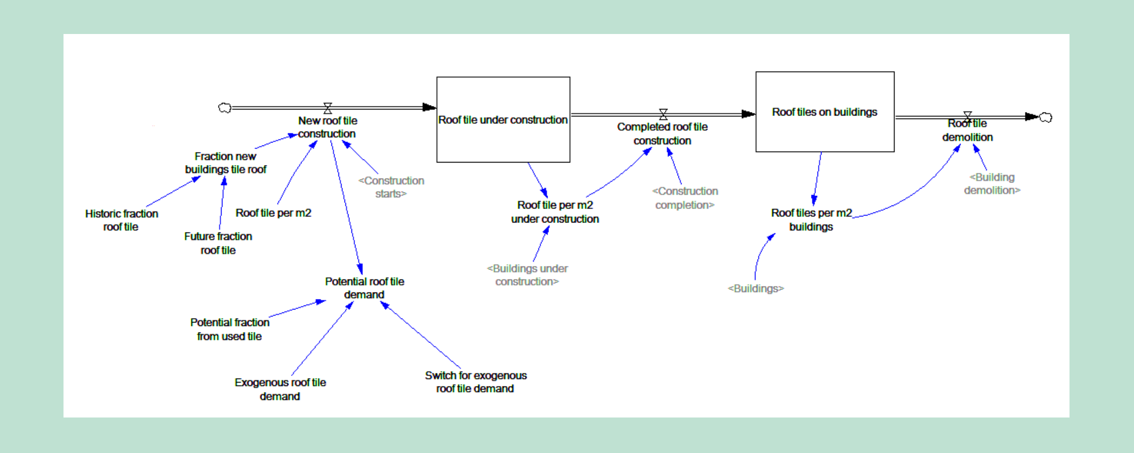


FIGURE 25. Model representation roof tiles embedded in existing buildings

That said, there are some historical data for the percentage of built structures that have roof tiles (see FIGURE 23). We see that roof tiles constituted about a third of all buildings constructed prior to World War II, but since then the fraction has dropped to about 10%. Nonetheless, roof tiles could play a significant role in renovation of existing buildings, particulary older classified buildings. Given the knowledge of the percentage of buildings using roof tiles, the share these buildings constitute of the total dwelling area, and the total number of roof tiles produced on average in Denmark (about 10-15 mio. pieces per year), the model infers a certain (fixed) number of roof tiles per new dwelling area built, which can be used for future forecasts of available used tiles. The estimate in the model is 10 tiles per floor square meter.

Once demolished, roof tiles in the model are either assumed to be disposed of in a **“conventional”** manner (crushed and use for base material, “stabilgrus”, or various niche applications such as substrate for green roofs) or they are cleaned, sorted, and inventoried for **re-use** as roof tiles.

Unlike the case of concrete, it is assumed that the ability of re-using roof tiles is not dependent upon the original design of the building but on a sufficient supply system of materials that have been properly cleaned, classified and registered for re-sale. In order to illustrate the development of such a system, it is simpler to simply assume a constant exogenous supply of demolished roof tiles over time and then examine how different initiatives may affect the market evolution. Thus, the model contains a switch between a simple exogenous flow of roof tiles from demolition, or an endogenous supply based on estimates of the tiles embedded in existing structures. In the scenarios described in Section 6.4 and 6.5, the exogenous flow is assumed.

Wood

In the case of wood materials, there are very few historical data on which to base the modelling. Therefore, the calculations for this part of the model are mostly based on qualitative scenarios with illustrative numbers. A proper analysis of the potential market for wood components would require an extensive further study, which is beyond the scope of this report. Nonetheless, the qualitative scenarios outlined in the main report can at least help point to some issue that will need to be addressed by the industry in the future.

Thus, while one could in principle provide a structure of embedded wood in existing buildings similar to that of concrete (FIGURE 22) and roof tiles (FIGURE 25), this structure has been excluded from the model until further data might become available. Moreover, as mentioned in Section 2.2.3, there is also a stream of waste wood coming from private discards of wooden material, e.g., furniture or minor private renovations, that consistutes a substantial fraction of the current amount of wood waste (about 1/3). Therefore, the supply of new wood for potential re-use or recycling is assumed to be exogenous and, for the most part, constant, as a way to illustrate a potential market that may or may not be realised.

The model ignores the part of wood waste that is impregnated, as this is assumed to be neither suitable for recycling nor re-use. The "clean" wood stream is assumed to either be treated in the **conventional** ways mentioned in Section 2.2.3, such as shredding for particle board manufacturing, exported for recycling abroad, or inceneration, or **re-used** as new building components, after some appropriate processing.

As mentioned in Section 2.2.3, at present, the re-use of wood products in buildings is very limited. Some elements like windows and doors may be re-used in renovations. Some lumber can be re-used directly after proper cleaning and sorting (removing nails, etc.). There are some initial attempts to shred wood for insulation material. In the U.S., there is an increasing use of wood that is shredded and laminated with various resins to form so-called Structural Composite Lumber that can potentially replace steel in new buildings.[16]

The assumption in the model is that large-scale re-use of wood would require the building up of the capacity to process, clean, register and inventory wood components suitable for future re-use. And in the case of structural composite lumber and other derivative wood products, it would require investments in R&D.

I.3 Modelling the C&DW markets

As mentioned above, the model attempts to represent the following dynamical market processes: 1) Learning curves, 2) scale economies, 3) scope economies, 4) market learning and adoption, and 5) security of supply. From a policy perspective, the model will be used to analyze the four policy initiatives identified by the project partners as most promising. Therefore, the market structures are represented in a way that at least to some extent allows for the effect of these policies. In the following, we first describe the model representation of demand, i.e., how buyers are assumed to act, given their perceptions of quality, security of supply and general "willingness to consider" new alternatives. Then we describe how the model's representation of the supply side is determined by investments and profitability as well as the processes that allow for the realization of scale and scope economies, and learning curve effects.

Demand side

For the most part, the demand side of the market is similar for all three waste fractions, except that for the case of recycled concrete aggregate (RA) where product stocks are not modelled explicitly since availability and scope economies are deemed less significant in this system than in the tile and wood systems. Wherever the formulations differ, it will be pointed out in the following.

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[16] See, e.g. https://www.fpl.fs.fed.us/documnts/techline/structural-composite-lumber.pdf or https://www.woodsolutions.com.au/wood-product-categories/structural-composite-lumber-scl.

On the customer side, demand for recycled materials is assumed to be driven both by the overall demand for materials (as a function of the current level of activity in the building industry) and by the relative attractiveness of the recycled product, compared to the conventional alternative (new cement, tiles or wood). Relative attractiveness is assumed to be influenced by the following main four factors:

1. Price
2. Quality (or reliability in quality)
3. Variety (scope)
4. Delivery security/time

Willingness to consider WtC

In addition to the four "classic" factors above, given that this is a new and relatively unproven product or process, there is a crucial additional factor at play, the "Willingness to Consider" (WtC). The idea is that the majority of market participants have a relatively conservative attitude towards trying out new products. Given the very substantial risks and potential liabilities involved in construction projects, buyers are reluctant to employ re-recycled or re-used products unless there is sufficient documentation, either in the form of product testing and certification or in the form of experience and reference value cases from other customers in the market. This introduces a classic self-reinforcing adoption cycle, often called "Word-of-mouth", where the number of market participants willing to consider the product is a function of the number of existing adopters, which is in turn driven by the number of new adopters, etc. etc.

The Willingness to Consider W is assumed to change gradually over time, increasing with "social exposure" and marketing efforts. Specifically,

$$\dot{W} = \frac{dW}{dt} = h(1 - W) + \kappa m(1 - W) - \frac{W}{\delta},$$

where W is the "willingness to consider", a dimensionless index between 0 and 1. The change over time $\dot{W}$ consists of three terms: The first term $h(1 - W)$ represents the effect of information campaigns or marketing efforts to raise awareness in the industry, typically initiated by government policy. The second term $\kappa m(1 - W)$ measures the effect of "social exposure" or direct evidence from market participants, or reference value cases provided by suppliers in the market. It is proportional to the market share of the new product m. The parameter κ measures the strength of this effect, which is a function both of the intensity of contacts between actors in the industry and the degree to which direct meetings or value cases lead to changes in their decisions. The final term expresses the idea that familiarity or willingness to consider may erode over time (with an average lifetime of δ). If all other factors are held constant, the typical behavior of W is an S-shaped curve, where more exposure to the new product leads to high market share, which in turns leads to even faster adoption, up to the point where the market becomes saturated ($W = 1$).

While both the concrete and the tiles markets have active market learning (WtC varies over time), for the wood market, we have chosen to remove this effect by assuming that the market is full aware. The rationale behind this choice, apart from reducing the amount of complexity in the analysis, was mainly to explore some of the other dynamics in this market, related to economies of scale, for instance. As mentioned previously, the scarcity of data for the wood market means that the analysis has more the character of hypothetical "what if" scenarios than any operational forecast. The choice to remove the WtC effect means that results will be somewhat on the optimistic side.

Product attractiveness and market share

Apart from the "word-of-mouth" effect, each of the four "classic" factors mentioned above in effect create a potential self-reinforcing feedback loop, as was illustrated previously in FIGURE 21. First, scale economies and learning curve effects will eventually drive down unit costs, allowing suppliers to charge lower prices, which will in turn spur further demand and room for more cost decreases. Second, higher market volume will afford a greater variety of different models, products, and qualities, which will in turn enhance the relative attractiveness of recycled or re-used products, allowing for further growth. Third, a higher volume will, all other things equal, lead to greater the reliability of supply and the lower the variance in delivery times. In the model, the delivery reliability is assumed to be directly related to the amount of material in stock with the suppliers: If stocks are low compared to the average sales volumes, the likelihood of stock-outs and delivery delays increase, reducing the demand for the product.

Ignoring for a moment whether the product can be delivered in time, the model defines a **perceived** relative attractiveness A of the new product as a dimensionless variable, where a value of 1 would indicate a perception that it is equivalent in attractiveness to the conventional product. A value of 0 would indicate a completely un-acceptable attractiveness, and a value above 1 would indicate that the product is perceived to be more attrac-tive than the conventional alternative. Specifically, we assume that

$$A = W \left(\frac{P}{P_A}\right)^{\pi} \left(\frac{Q}{Q_A}\right)^{\theta} \left(\frac{K}{K_A}\right)^{\rho},$$

where P is the unit price, compared to the alternative price P_A, Q is an index of perceived "quality", compared to a reference value or an alternative Q_A, and K is the overall capacity of supply, compared the a reference value K_A. The latter is assumed to capture the effect of scope economies on perceived attractiveness: the larger the capacity of supply, the wider the variety. The three coefficients, $\pi < 0, \theta > 0, \rho > 0$ measure the relative im-portance of price, quality and variety (scope) in determining attractiveness, respectively. Clearly, this is a highly simplified choice model, but for the purposes of this exploratory model, it is deemed to be appropriate. The factor W captures the overall "willingness to consider" or "familiarity" factor. Thus, a value of $W = 1$ would indi-cate that the market is fully able and willing to consider the new product on par with existing alternatives. A value of $W = 0$ would indicate that buyers are completely unaware of or unwilling to consider the new product.

In order to translate the relative attractiveness A into an indicated market share m, we propose a sigmoid func-tion of the form

$$m(A) = a + \frac{b-a}{1 + d\, e^{-cA}}, \qquad c > 0.$$

We specify the parameters a, b, c, d in the function by fixing the following three reference points: the minimum market share (if attractiveness is zero) $m(0) = m_0$, the reference market share (if attractiveness is equal to the alternative) $m(1) = m_1$, and the maximum market share (if the new product is much more attractive than the alternative, $m(\infty) = m_\infty$. Furthermore, the parameter c specifies how sensitive the market is the deviations in relative attractiveness. FIGURE 26 shows a plot of $m(A)$ for $m_0 = 0, m_1 = 0{,}9, m_\infty = 1$ for various values of the sensitivity parameter c. The value chosen for the simulations is $c = 10$.

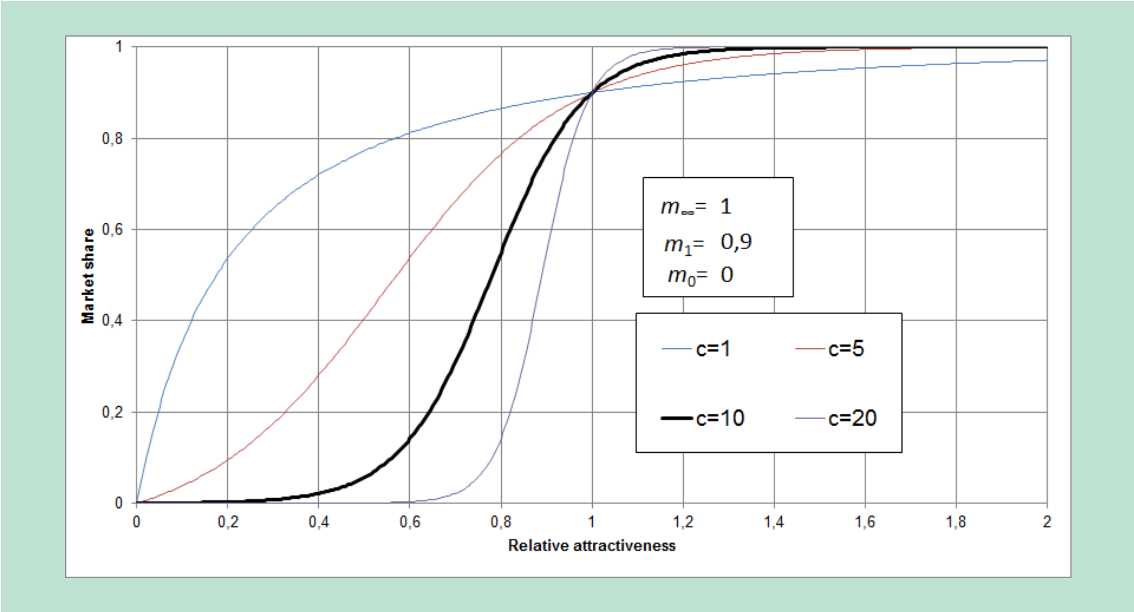

FIGURE 26. Plot of m(A) for various values of the sensitivity parameter c

Product availability and supply constraints

Finally, actual delivery is a function of current demand D but constrained by the available supply. In the case of wood and tiles, supply is a function of the amount of inventory on hand of the material. Actual sales or shipments X is the demand (determined by total potential demand and the market share factors above), multiplied an "effect of availability",

$$X = Df(S),$$

where the effect of availability is a function of the relative availability or stock S: the inventory on hand N relative to the stock required to deliver current demand with a required normal inventory coverage ν, measured in years. Specifically, the effect is formulated as

$$f_S(S) = (1+\sigma)\frac{S}{\sigma + S}, \qquad S = \frac{N}{\nu\, D^*}$$

where σ is a dimensionless parameter that measures the sensitivity of demand or delivery to available stock. FIGURE 27 shows a plot of the function f_S for various values of σ.

In the case of recycled concrete aggregate (RA), the situation is a bit different, since the aggregate is readily substitutable with virgin material. Therefore, availability is less likely to play a role in demand. Consequently, the flow of material is determined by the processing capacity of the recycling facilities, whereas stocks of recycled aggregate are ignored. In the case of modular concrete (not considered explicitly in this analysis), the stock of modules in stock would indeed play an important role (as would variety and economy of scope). Therefore, the model does include a latent structure to keep track of stocks of modular concrete and the effect of availability on demand with a similar effect to the one shown in FIGURE 27.

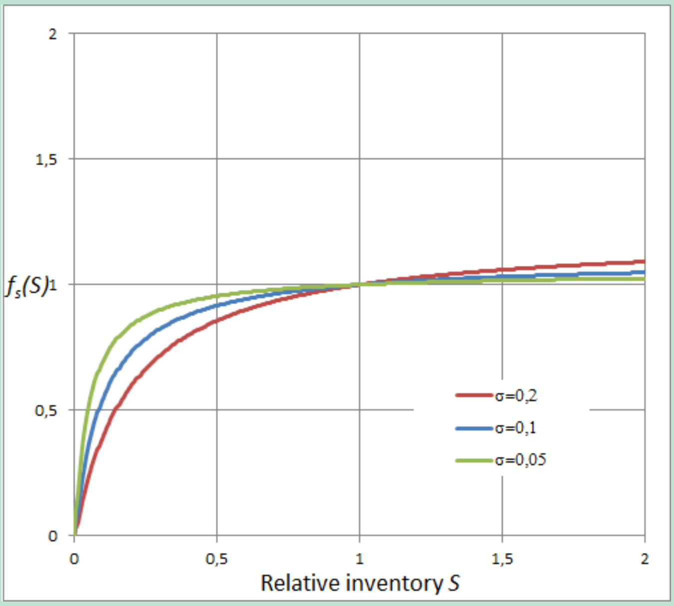

FIGURE 27. Plot of the effect of available inventory on demand or delivery

TABLE 9 lists the default values of the parameter values used for the demand side in the model.

TABLE 9. Default demand parameter values

Parameter (Unit of quantity	Concrete (RA) (tonnes)	Roof tiles (T) (pieces)	Wood (W) (tonnes)
κ, strength of social exposure (diml.)	1	1	n/a
δ, lifetime of social exposure (years)	∞	∞	n/a
$W(0)$ initial value of familiarity (diml.)	0.1	1	n/a
π, price sensitivity (diml.)	-1.5	(varies)	0
θ, quality sensitivity (diml.)	0.5	0	0
ρ, scope or range sensitivity (diml.)	0	0	0
c, overall sensitivity of demand (diml.)	10	10	10
m_0 minimum market share (diml.)	0	0.01	0.01
m_1 parity market share (diml.)	0.9	0.7	0.7
m_∞ max market share (diml.)	1	1	1
P_A, alternative price (DKK/unit)	190	20	n/a
Q_A, alternative quality (diml.)	1	1	1
K_A, reference scope capacity (units/year)	n/a	1 mio.	1 mio.
ν, normal inventory coverage (years)	n/a	1	1
σ, sensitivity to inventory (diml.)	n/a	0.2	0.2

Supply side

The supply side is modelled somewhat differently for the three waste fractions, reflecting the assumptions that different factors are at play in the evolution of the market for the three. However, some elements are also common to all three sectors. We begin with the modelling of capacity and output, which is assumed to be similar for all three.

Capacity investments

For all three sectors, supply of the product is assumed to depend on investments in processing capacity, distribution logistics, marketing and administration, etc. These elements are all aggregated into a single aggregate "capacity" measure. This capacity is a stock that is increased by new investments and decreased by depreciation. The latter is assumed simply to be proportional to capacity, with an average lifetime of τ_C. Investments I in new capacity are formulated as

$$I = \max\left(0, \frac{K}{\tau_C} + \frac{K^* - K}{\tau_K}\right),$$

where K^* and K is the target and current actual capacity, respectively, and τ_K is an adjustment time. In other words, investments are made to both replace existing depreciation of capacity and to adjust capacity towards a target value over some period of time. Furthermore, gross investments are constrained to be non-negative.

Target capacity is driven by both "price signals" and "quantity signals". Thus, investors are assumed to come up with some notion of expected demand or output (the "quantity signal"), modified by an effect of the average profit mark-up (the "price signal"). A positive (above normal) economic profit will lead to a higher target output, and vice versa.

Expected future demand or output D_E is assumed to be based on recent demand, essentially a historic moving average D_H with an averaging time of τ_E. As a test case, it is also possible to introduce an element of exogenous (autonomous) expectations D_X of future demand, as government by the "weight on history" w_H.

$$D_E = w_H D_H + (1 - w_H) D_X,$$
$$\dot{D}_H = (D - D_H)/\tau_E,$$

This is to explore the possibility that the market may be locked into a trap of low demand expectations leading to low investments in capacity, constraining sales, which in turn keeps demand low to make the low expectations self-fulfilling. An autonomous element of future demand could for instance be the announcement of a concerted effort by government to enhance the market, e.g. through green public purchasing (GPP).

Target capacity is further potentially constrained by available raw material R from demolition, but is also influenced by high prices and profitability (the price signal). Thus, the formulation for target capacity K^* is

$$K^* = \min(D_E, R)\, M_H^{\varepsilon_M},$$
$$\dot{M}_H = (M - M_H)/\tau_M,$$

where M_H is a long-term historical moving average of the mark-up (ratio) M of price over unit cost, with an averaging time τ_M is the averaging time, and the parameter ε_M is the medium-run "price elasticity of supply".[17] In many of the simulations, the price mediation is assumed to be inactive, i.e., ε_M is assumed to be zero so that the medium-term supply of the market is instead mediated entirely by quantity signals (orders, stocks, inventories, etc.).

Output

In the short run, output will be constrained by current capacity. It is assumed that there is some degree of flexibility of supply in the short run (e.g. by running extra shifts on the factory). Specifically, we assume that if the desired output is Y^* and the capacity is K, the actual output will be

[17] Costs are assumed to be full economic costs, including capital charges, opportunity costs, etc. Thus, in market equilibrium, prices would equal unit costs. The elasticity of supply here is a medium term measure showing how much output would increase if prices remain at their current levels for some time. The long-term elasticity is much higher (essentially infinite) as long as the supply is not constrained by the available of waste materials from demolition. The short-term supply elasticity (for a given level of capacity) is captured in the formulation for price markup (see below).

$$Y = Kf\left(\frac{Y^*}{K}\right), \qquad f(r) = \frac{(1+\gamma)}{\gamma + r} r, \qquad \gamma \geq 0.$$

FIGURE 28 shows a plot of the function $f(r)$ for various values of the parameter γ.

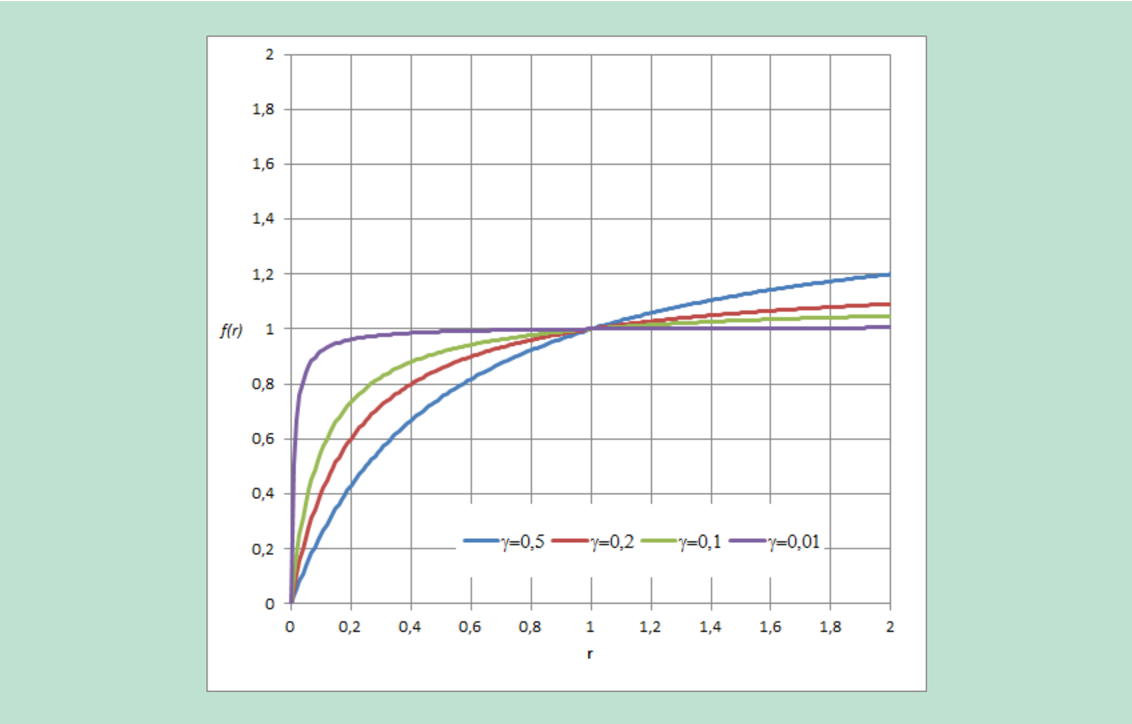

FIGURE 28. Plot of the capacity utilization function $f(r) = r(1+\gamma)/(\gamma + r)$ for various values of the flexibility parameter γ.

Desired output Y^* in turn is formulated slightly differently for the three sectors. For all three, it reflects current demand D. In addition, for all three there may be a constraint of available raw material R from demolished buildings or renovations on output, even if there is sufficient capacity. For tiles and wood, which also explicitly represent inventory stocks of finished product, there may be an additional component of stock adjustment to the desired output. In short, for recycled aggregate, desired output is

$$Y^* = \min(R, D),$$

whereas for tile and wood it is

$$Y^* = \min\left(R, D + \frac{N^* - N}{\tau_N}\right),$$

where N^* and N is the target and current inventory stock, respectively, and τ_N is the time to adjust inventory to target levels. Given production Y and product shipments or sales X (considered in the description of demand in Section 8.6.1.3 above), the stock N evolves according to

$$\frac{d}{dt}N = \dot{N} = Y - X.$$

The desired or normal stock is assumed to be proportional to the demand,

$$N^* = \nu\, D,$$

where the parameter ν is the normal inventory coverage, measured in years.

Short run pricing

In the short run, prices are assumed to reflect unit cost UC, multiplied by a mark-up factor M. The latter is assumed to reflect current demand-supply conditions, as measured by the demand D relative to current capacity K. (Short-term stock-outs are not assumed to affect prices but are instead affecting purchases directly.) Firms are assumed to adjust their mark-ups gradually to the target M^* over some months, reflected in the time constant τ_M. In other words

$$P = UC \cdot M$$
$$\dot{M} = (M^* - M)/\tau_M,$$
$$M^* = f(D/K).$$

The following formulation was chosen for the indicated mark-up function

$$f(r) = r^{1/\varepsilon_S},$$

where $\varepsilon_S > 0$ can be thought of as the short-run elasticity of supply. A high value would mean that prices do not vary much while a low value would lead to more variation in prices. FIGURE 29 shows some plots of the function $f(r)$ for various values of the parameter ε_S. By default, the price mechanism is deactivated by setting it to a very large number, essentially $\varepsilon_S = \infty$, meaning prices do not change at all in response to demand-supply short term imbalances ($f(r) = 1$).

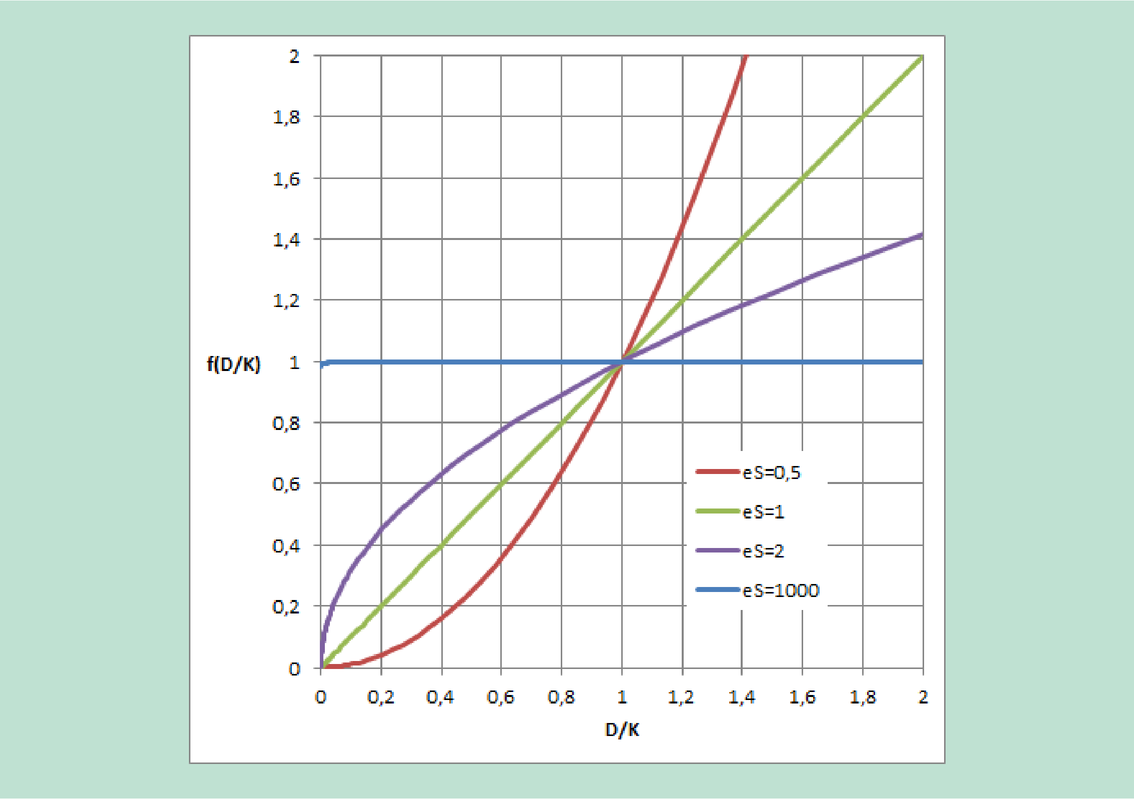

FIGURE 29. Plot of the indicated mark-up of prices over unit cost, as a function of relative demand, for various values of the short-run elasticity of supply ε_S

Long-run costs and prices

The unit cost of production is assumed to be affected by both scale economies and learning curves. Specifically, we assume that unit cost are

$$UC = UC_0 \cdot \left(\frac{K}{K_0}\right)^{-\alpha} \left(\frac{E}{E_0}\right)^{-\frac{\ln \lambda}{\ln 2}},$$

where UC_0 is the reference unit cost, K is the current supply capacity, K_0 is the reference capacity, E is the production experience, measured as the current cumulative output, E_0 is the reference production experience, α is a parameter measuring the strength of the scale economy effect, and λ is a parameter measuring the strength of the learning curve effect. For a 10 % learning curve where cost go down by 10 % for each doubling in cumulative production, we would set $\lambda = 0.9$. Experience E accumulates with production but is also potentially subject to erosion over time, as experience becomes less relevant. In other words, cumulative experience evolves according to

$$\frac{dE}{dt} = \dot{E} = Y - \frac{E}{\tau_L},$$

where Y is production and τ_L is the average lifetime of experience, set at 10 years for all three sectors. At the outset, the learning curve effect is deactivated by setting $\lambda = 1$ and the scale economies are ignored by setting $\alpha = 0$. Unfortunately, we were not able within the scope of the project to obtain sufficient data to assess these parameters.

Supply of virgin aggregate (VA)

The model also includes the potential depletion of virgin aggregate resources for concrete (excavated gravel and sand). This can be significant to the extent that rising prices of virgin aggregate can affect the demand for recycled aggregate as an alternative (remember that demand is determined by the relative price of the two.) Given that sand and gravel is a non-renewable resource and that there are increasing signs of shortages of this natural resource, it is relevant to include this as a possible factor in the scenarios. The model operates with a fixed stock of virgin material resource that is depleted by whatever material is used in current production of new concrete that is not based on recycled aggregate. It is assumed that as this stock is depleted, the price of virgin aggregate will rise. Given that the market share of recycled aggregate is a function of the relative price of recycled versus virgin aggregate, this will affect the demand in the model for recycled aggregate. The specific equation for the price of virgin aggregate P_V in the model is

$$\frac{P_V}{P_0} = \frac{1}{r}\frac{\psi + r}{1 + \psi}, \qquad r = \frac{V}{V_0},$$

where P_0 is the reference or initial cost, and V_0 and V is the intial and the remaining virgin aggregate stock, respectively, and ψ is a parameter expressing the strength of the resource scarcity effect on cost. FIGURE 30 shows a plot of $\frac{P}{P_0}$ as a function of $\frac{V}{V_0}$ for various values of the parameter ψ.

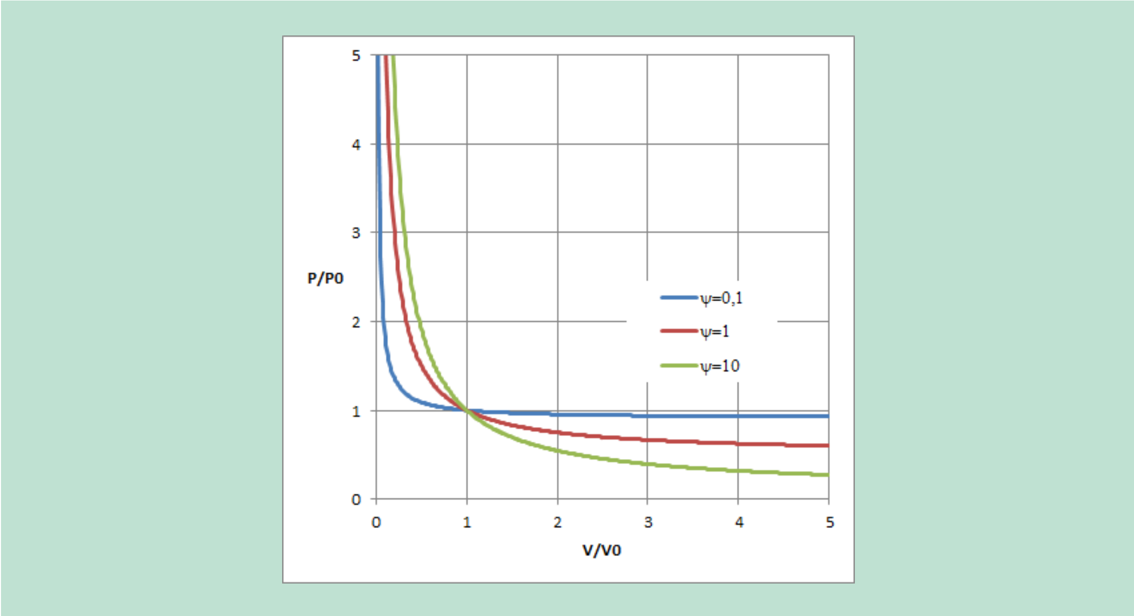

FIGURE 30. Plot of the relative cost of virgin aggregate P/P_0 as a function of the remaining fraction of virgin resource V/V_0 for various values of the resource scarcity parameter ψ

TABLE 10 lists the default supply parameter values used in the model.

TABLE 10. Default supply parameter values

Parameter (units of measurement)	**Concrete (RA)** (tonnes)	**Roof tiles (T)** (pieces)	**Wood (W)** (tonnes)
τ_C average lifetime of capacity (years)	5	10	10
τ_E time to average historic demand (years)	1	2	2
τ_H time to average mark-up history (years)	2	1	1
τ_M time to adjust mark-up	0.25	.25	.25
ε_M medium term elasticity of supply (diml.)	0.001	0.001	0.001
ε_S short term elasticity of supply (diml.)	∞	∞	∞
UC_0 reference unit cost (DKK/unit)	150	20	20
γ flexibility in output (diml.)	0.1	0.2	n/a
α strength of scale economy effect (diml.)	0	0	0
K_0 reference capacity for scale (units/year)	100	1 mio.	1 mio.
λ learning curve factor (dimensionless)	1	1	1
Y_0 reference output experience (units)	100	∞	∞
τ_L average lifetime of experience (years)	10	10	10
P_0 initial cost of virgin aggregate (DKK/unit)	190	n/a	n/a
V_0 initial stock of virgin aggregate (units)	∞	n/a	n/a
ψ strength, resource scarcity effect (diml.)	0.1	n/a	n/a
S_T exog. roof tiles available (units/year)	n/a	6 mio.	n/a
τ_N time to adjust inventory (years)	n/a	1	
ν desired inventory coverage (years)	n/a	1	
τ_K time to adjust capacity	2	2	

Market flows

The actual quantities recycled, re-used or disposed of in the traditional manner are a function of both the demand and the supply side of the market. For all three waste fragments, the supply side of the market is limited by the available waste from demolition. In the case of concrete, it is assumed that all concrete arising from demolition of buildings is in principle available for processing into either of the three pathways mentioned before, recycled aggregate (RA), modular redeployment (MC), or traditional disposal as filler and road base. The modular redeployment requires that the building was originally designed for this purpose and is currently inactive in the model. It is further assumed that there is a maximum potential fraction of the concrete that can be recycled as aggregate (RA), given constraints on purity, quality, and feasibility in processing. At present, this maximum is set at 20 %. Whatever is not recycled in this manner is instead disposed of in traditional ways, in other words, the model calculates the traditional disposal as a residual from the part of the market that goes into recycled aggregate. In case the modular concrete sector of the model is activated, this part of the material concrete flow would then also be subtracted from whatever is available for traditional disposal or recycled aggregate.

I.4 Implementing policy scenarios

In this section, we describe how the four elements of the idea catalogue are implemented in the model. First, though, it is appropriate to provide some general considerations on the dynamical properties of the market system which are in some sense implicit in many of the considerations underlying the policy suggestions.

What is apparent when you consider the structures involved in the model of the C&DW markets is that they involve a number of self-reinforcing feedback effects ("positive feedback loops"). This was already alluded to in the description of the modelling approach and illustrated in FIGURE 21. First, the model assumes that one of the main barriers to market development is a "wait and see" attitude among buyers of secondary materials. Thus, the "Willingness to Consider" or WtC plays a key role in buyers' assessment of the relative quality and potential cost of these unknown inputs. Given the significant risks involved if materials turn out not to live up to the required technical properties or that there are problems with toxic substances in the materials, it not unreasonable on the part of customers in the market to want to see proper proof and assurance that the quality of the product is indeed OK. Yet sufficient evidence of this requires a certain amount of market experience, so the more experience and evidence you get in the market, the more demand there will be for the product, which in turns leads to further cumulative experience, etc.

Another important positive feedback relates to economies of scope. For products like roof tiles or wood components that are not recycled as inputs to other products, the specific form factor of the product (dimensions, colour, etc.) will be important when buyers consider secondary products. But given the variety in demand for the product along these dimensions, it is crucial for the functioning of the market that there is a sufficient selection of varieties. Otherwise, it will too often be the case that no second-hand product matches the particular demand of the customer at the time when it is needed. This implies that the larger the volume in the market, the more room there is for variety in products, which in turn has a strong effect on demand, in turn affecting future volume expansions. Another way to look at this is that suppliers must invest in a relatively large stock of secondary materials if they are to satisfy the demand for variety.

A third factor relates to economies of scale: The larger the volume of production, distribution and marketing of the materials, the lower the average unit cost per item. Again, this introduces a self-reinforcing feedback effect where larger volume leads to low costs and therefore prices, which in turn expands demand, leading to still larger volume.

While these self-reinforcing loops represent powerful drivers of market development once they are set in motion, they also represent tremendous inertial barriers to overcome. Unless the market can be brought to an effective scale and scope, it may be at least risky if not financially impossible for entrepreneurs to establish new businesses. As a result, the system may settle into a condition where no-one is able or willing to risk the investments required to realise this market. What is required is some form of outside factor that will make it less uncertain that the market will develop.

In many ways, the policy initiatives considered to establish the secondary materials markets can be seen as attempts to activate these positive feedback loops. To restate, the four initiatives deemed most effective by the working group were

5. **Certification schemes, product warranties, and "material passports".** The rationale is that this would improve the confidence of buyers in the technical quality of the product, as well as minimizing perceived risks of either technical shortfalls or possible environmental problems.
6. **Matching and market-making trading platform.** The main purpose of this would be to heighten the visibility of secondary materials markets and improve the information efficiency of the market, leading to better allocations of materials to local customers, thus minimizing transportation costs. Moreover, the expectation is that the platform would increase the market volume, leading to lower costs and better scope economies.
7. **Demonstration projects with focus on costs and benefits**. The main purpose would be both to generate more knowledge of costs and issues in operating the market, and a documentation of possible benefits that would be directly relevant to decision makers on the demand side.
8. **Green public procurement**. Apart from signalling the importance of re-cycling and re-use and serving as a basis for gaining experience, the main effect would be to provide a minimum demand for secondary materials that could serve as a seed for the formation of a private commercial market.

The modelling scenarios are performed to explore the effects of each of these four initiatives by comparing them to a base case where no such initiatives are performed. The question of interest is mainly whether they are each sufficient to provide a turn-around of the market, or whether they need to be used in some combination. In the following, we describe how each initiative is translated into concrete parameter changes in the model.

The first three initiatives all work to bolster the confidence in the new materials and to provide better information on costs, quality, etc. In the model, this is interpreted as a factor that increases the Willingness to Consider factor among buyers and potentially also the perceived quality of the product, since certification allows for a better differentiation among products. This may be implemented concretely by interpreting the effort as a "marketing" or information campaign that adds to the WtC stock.

Certification schemes also serve to improve the actual quality in that it reduces the risk variability in the properties of the product, itself an important element of quality. In the model, this can be implemented as an increase in the quality factor entering product attractiveness.

There are of course also costs associated with the certification and documentation itself, and it may lead to higher discard rates of unacceptable products. As the cost and scale economy figures are already highly uncertain, we chose to exclude this additional effect from consideration at this stage.

To some extent, the second initiative, market matching platforms, also serves to lower average costs, both by minimizing average transportation, by minimizing the required inventory of material on hand to provide the same level of supply availability, and by providing a better match with buyer demands (quality): All other things equal, if it is easier to locate specific materials somewhere in the market, there is less chance of stock-outs for a given average level of inventory holdings. In the model, this is implemented as a combination of a lowering of the required inventory coverage to provide the same level of supply security and an improvement in average quality.

Moreover, the second initiative may affect the economy of scope effect on the market: with an efficient information exchange platform, the volume and inventory required to provide sufficient variety for customers may all other things be less when it is easy for them to locate specific items. This is particularly true if the system can to some extent be made forward-looking, anticipating the provision of used building components before demolition. In the model, this is implement as a reduction in the requisite scale to afford a given level of scope economy or variety.

Finally, the matching platform itself serves to enhance the visibility of the market, hence promoting faster market learning through the WtC mechanism. In the model, this can be represented by increasing the strength of social exposure (the parameter κ).

The third initiative, demonstration projects with costs and benefits, creates more transparency in the market and provides documentation for proven results. In this manner, the main effect would be to raise market awareness and the willingness to consider the new products. Hence one would primarily implement this in the model by increasing WtC via the equivalent of a "marketing" campaign.

The fourth initiative, green public procurement (GPP), has a different effect in that it adds a less elastic component of demand for the secondary material. In the model, we accommodate this by assuming that a certain fraction of demand (GPP market share) is governed by procurement regulation and therefore is not sensitive to issues such as price, quality or delivery delay. Here, we are assuming that the basis of comparison is between the secondary material and the conventional alternative, not between alternative suppliers of secondary material, where there may indeed be competition in bidding for these GPP contracts.

TABLE 11 summarizes the translation of the initiatives in to model parameter changes

TABLE 11. Model parameter changes and policies

Parameter	#1: Certification	#2: Trading platform	#3: Value demonstration	#4: GPP
h: marketing effect on WtC	+	+	+	
κ strength of word-of-mouth	+	+	+	
Q quality	+			
ν required inventory coverage		-		
Reference unit cost		-		
Reference scope capacity		-		
Autonomous demand component				++

Appendix 2. Model equations

Variable	Definition	Units [Range]	Comment
a T=	(b T*EXP(c T)*m0 T-b T*m1 T+m0 T*m1 T-EXP(c T)*m0 T*m1 T)/(b T*(EXP(c T)-1)+m0 T-EXP(c T)*m1 T)	Dmnl	
a W=	(b W*EXP(c W)*m0 W-b W*m1 W+m0 W*m1 W-EXP(c W)*m0 W*m1 W)/(b W*(EXP(c W)-1)+m0 W-EXP(c W)*m1 W)	Dmnl	
Aggregate requirement=	0.8	Dmnl	Tonnes of aggregate per ton of finished concrete
Alpha RA=	0	Dmnl [0,1,0.01]	Scale coefficient. Measures the strength of scale economies from none (value of 0) to 100 % (value of 1) where there is a single fixed investment with zero marginal capacity cost.
alpha T=	0	Dmnl	Strength of scale economy effect
alpha W=	0	Dmnl [0,2,0.1]	Strength of scale economy effect
Alternative value of RA=	0	Dmnl	The alternative value of RA is reflected in the price it currently fetches on the market
aRa=	(bRA*EXP(cRa)*m0 RA-bRA*m1 RA+m0 RA*m1 RA-EXP(cRa)*m0 RA*m1 RA)/(bRA*(EXP(cRa)-1)+m0 RA-EXP(cRa)*m1 RA)	Dmnl	Parameter in market share function
Autonomous expected demand T=	Policy switch T*Fraction of potential autonomous T*Potential demand T	Stk/Year	
Autonomous expected demand W=	Policy switch W*Fraction of potential autonomous W*Potential demand W	Ton/Year	
Availability of virgin material resource=	Virgin material resource/Initial virgin material resource	Dmnl	Index of availability of virgin resource
Avg building lifetime=	85	Years [0,100,1]	
Avg construction time=	1.25	Years	
Avg processing time of demo concrete=	0.25	Years	Avg processing time of conv demo concrete
b T=	mmax T	Dmnl	
b W=	mmax W	Dmnl	
bRA=	mmax RA	Dmnl	Parameter in f(x)
Building demolition=	Buildings/Avg building lifetime	M2/Year	
Buildings=	INTEG(Construction completion-Building demolition, Initial buildings)	M2	Assumed to be in steady state initially
Buildings under construction=	INTEG(Construction starts-Construction completion, Historic buildings under construction)	M2	Assumed to be in steady state initially
c T=	10	Dmnl	Sensitivity of demand to attractiveness

c W=	10	Dmnl	Sensitivity of demand to attractiveness
Capacity depreciation RA=	Policy switch for RA*Capacity RA/tauC RA	Ton/(Year* Year)	
Capacity depreciation T=	Policy switch T*Processing capacity T/tauC T	Stk/Year/Y ear	
Capacity depreciation W=	Policy switch W*Processing capacity W/tauC W	Ton/Year/ Year	
Capacity investments RA=	Policy switch for RA*MAX(0,Capacity RA/tauC RA+(Target capacity RA-Capacity RA)/tauK RA)	Ton/Year/ Year	
Capacity investments T=	Policy switch T*MAX(0,Capacity depreciation T+(Target capacity T-Processing capacity T)/tauK T	)	Units: Stk/Year/Year
Capacity investments W=	Policy switch W*MAX(0,Capacity depreciation W+(Target capacity W-Processing capacity W)/Investment time tile capacityW)	Ton/Year/ Year	
Capacity RA=	INTEG(Capacity investments RA-Capacity depreciation RA, 0)	Ton/Year	
Capacity utilization RA=	(1+gamma RA)*Indicated capacity utilization RA/(gamma RA+Indicated capacity utilization RA)	Dmnl	Effect of availability (security of supply) on attractiveness of recycled aggregate
Capacity utilization T=	(1+gamma T)*Indicated capacity utilization T/(gamma T+Indicated capacity utilization T)	Dmnl [0,1.5]	
Capacity utilization W=	(1+gamma W)*Indicated capacity utilization W/(gamma W+Indicated capacity utilization W)	Dmnl	
CC per M2=	Concrete in buildings CC/Buildings	Ton/M2	
CC per M2 under construction=	Concrete under construction CC/Buildings under construction	Ton/M2	
Completed construction T=	Construction completion*Roof tile per m2 under construction	Stk/Year	
Concrete available for recycling=	Concrete available for recycling CC+Concrete available for recycling MC	Ton/Year	
Concrete available for recycling CC=	Max potential recycle fraction of concrete*Processing of conv demo concrete	Ton/Year	
Concrete available for recycling MC=	(Processing of demolished modular concrete-Reuse MC)*Max potential recycle fraction of concrete	Ton/Year	Whatever modules are not re-used are available for recycling or traditional disposal
Concrete in buildings CC=	INTEG(Construction completion CC-Demolition CC, Buildings*Standard design concrete per M2*(1-Initial fraction of construction modular)*Fraction concrete)	Ton	
Concrete in buildings MC=	INTEG(Construction completion MC-Demolition MC, Buildings*Standard design concrete per M2*Initial fraction of construction modular*Fraction concrete)	Ton	
Concrete under construction CC=	INTEG(Construction starts CC-Construction completion CC, Buildings under construction*(1-Initial fraction of construction modular)*Standard design concrete per M2*Fraction concrete)	Ton	
Concrete under construction MC=	INTEG(Construction starts MC+Redeployment MC-Construction	Ton [0,1e+07]	

	completion MC, Buildings under construction*Initial fraction of construction modular*Standard design concrete per M2*Fraction concrete)		
Construction completion=	Buildings under construction/Avg construction time	M2/Year	
Construction completion CC=	Construction completion*CC per M2 under construction	Ton/Year	
Construction completion MC=	Construction completion*MC per M2 under construction	Ton/Year	
Construction starts=	IF THEN ELSE(Time<HistoryEndTime,Historic Construction starts,Future construction starts)	M2/Year	
Construction starts CC=	New concrete construction*(1-Fraction new concrete modular)	Ton/Year	
Construction starts MC=	New concrete construction*Fraction new concrete modular	Ton/Year	
cRa=	10	Dmnl	Paramter in market share function (see model description)
Cumulative production of RA=	INTEG(Production RA-Experience loss RA, Reference cumulative production RA)	Ton	Cumulative production for experience (learning curve) effects RA
d T=	(b T-m0 T)/(m0 T-a T)	Dmnl	
d W=	(b W-m0 W)/(m0 W-a W)	Dmnl	
Decay of WtC RA=	WtC RA/Lifetime of consideration	Dmnl/Year	Decay of familiarity
Decay of WtC T=	WtC T/delta T	Dmnl/Year	Decay of familiarity
delta T=	1e+06	Years	Decay time for familiarity (due to obsolesence or forgetting). Turned off by setting default to very high value.
Demand for aggregate=	Aggregate requirement*New concrete construction starts	Ton/Year	Demand for aggregate
Demand RA=	Demand for aggregate*Indicated market share of RA*Policy switch for RA	Ton/Year	
Demand T=	Potential demand T*Indicated market share T*Policy switch T	Stk/Year	
Demand W=	Potential demand W*Indicated market share W*Policy switch W	Ton/Year	
Demolished concrete CC=	INTEG(Demolition CC-Recycling CC-Traditional disposal CC, Demolition CC*Avg processing time of demo concrete)	Ton	
Demolished concrete MC=	INTEG(Demolition MC-Recycling MC-Reuse MC-Traditional disposal MC, Demolition MC*Avg processing time of demo concrete)	Ton	
Demolition CC=	Building demolition*CC per M2	Ton/Year	
Demolition MC=	Building demolition*MC per M2	Ton/Year	
Demolition of concrete=	Demolition CC+Demolition MC	Ton/Year	
Demolition T=	Building demolition*Roof tiles per m2 buildings	Stk/Year	
Desired processing	Demand T+Stock adjustment T	Stk/Year	

T=			
Desired processing W=	Demand W+Stock adjustment W	Ton/Year	
Desired stock T=	Demand T*nu T	Stk	
Desired stock W=	Demand W*nu W	Ton	
dRA=	(bRA-m0 RA)/(m0 RA-aRa)	Dmnl	Parameter in market share function
Duration of marketing campaign RA=	5	Years [0,10,1]	Duration of the marketing or information campaign. A policy parameter.
Duration of marketing campaign T=	5	Years [0,10,1]	Duration of the marketing or information campaign. A policy parameter.
E0 T=	1e+09	Stk	Reference cumulative output for learning curve effect
E0 W=	1e+09	Ton	Reference cumulative output for learning curve effect
Eff of inventory on sales T=	(1+sigma T)*Relative inventory T/(sigma T+Relative inventory T)	Dmnl	
Eff of inventory on sales W=	(1+sigma W)*S W/(sigma W+S W)	Dmnl	
Effect of availability on modular concrete=	(1+Sigma MC Sensitivity of modular demand to availability)*(1-(Sigma MC Sensitivity of modular demand to availability/(1+Sigma MC Sensitivity of modular demand to availability))^Relative availability of modular concrete)	Dmnl	
Effect of availability on price of VA=	(Strength of scarcity effect+Availability of virgin material resource)/(1+Strength of scarcity effect)/Availability of virgin material resource	Dmnl	Effect of scarcity on price of virgin aggregate (see model description).
Effect of learning on cost of RA=	(Cumulative production of RA/Reference cumulative production RA)^(LN(Learning coefficient RA)/LN(2))	Dmnl	Learning curve effect -- reduces cost by a constant factor with every doubling of production
Effect of marketing effort=	IF THEN ELSE(Time<Start time of marketing campaign RA, 0, IF THEN ELSE(Time>Start time of marketing campaign RA+Duration of marketing campaign RA,0, Size of marketing campaign RA))	Dmnl/Year	
Effect of marketing effort T=	IF THEN ELSE(Time<Start of marketing campaign T, 0, IF THEN ELSE(Time>Start of marketing campaign T+Duration of marketing campaign T,0, Size of marketing campaign T))	Dmnl/Year	
Effect of marketing on WtC RA=	Effect of marketing effort*(1-WtC RA)	Dmnl/Year	Fractional increase in WtC from marketing (information) campaigns etc.
Effect of marketing on WtC T=	Effect of marketing effort T*(1-WtC T)	Dmnl/Year	Fractional increase in WtC from marketing (information) campaigns etc.
Effect of markup on capacity T=	Historic markup T^epsilonM T	Dmnl	
Effect of markup on output W=	Historic markup W^epsilonM W	Dmnl	
Effect of markup on target capacity RA=	Historical markup RA^epsilonM RA	Dmnl	Supply responds to relative profitability, as measured by the historical markup factor, with a constant elasticity.
Effect of price RA attractiveness=	Relative price of recycled aggregate^(-pi RA)	Dmnl	Effect of price on attractivness of recycled aggregate

Effect of quality on RA attractiveness=	Perceived relative quality of RA^Sensitivity of RA to quality	Dmnl	Effect of quality on attractivness recycled aggregate
Effect of scale economy on cost of RA=	IF THEN ELSE(Capacity RA<K0 RA,1,(Capacity RA/K0 RA)^-(Alpha RA))	Dmnl	
Effect of social exposure on WtC RA=	RA market share*kappa RA*(1-WtC RA)	Dmnl/Year	Change in WtC from social exposure (word-of-mouth, seeing it in practice).
Effect of social exposure on WtC T=	Market share T*kappa T*(1-WtC T)	Dmnl/Year	Change in WtC from social exposure (word-of-mouth, seeing it in practice).
epsilonM RA=	0.001	Dmnl	Elasticity of supply measures the degree to which suppliers respond to price signals (profitability). A value of zero would mean they do not expect (or do not respond to) above or below normal returns but only respond to quantity signals.
epsilonM T=	0.001	Dmnl	Medium term price elasticity of supply
epsilonM W=	0.001	Dmnl	Medium term elasticity of supply
epsilonS RA=	1e+09	Dmnl [1,3,0.01]	Short run elasticity of supply
epsilonS T=	1e+09	Dmnl	Short term elasticity of supply
epsilonS W=	1e+09	Dmnl	Short term elasticity of supply
Exogenous demand T=	1e+07	Stk/Year	
Exogenous roof tile demo supply=	6e+06	Stk/Year	
Expected future demand RA=	SMOOTH(Demand RA, tauE RA)	Ton/Year	
Expected future demand T=	Historic demand T*wH T+Autonomous expected demand T*(1-wH T)	Stk/Year	
Expected future demand W=	Historic demand W*wH W+Autonomous expected demand W*(1-wH W)	Ton/Year	
Experience decay T=	Experience T/tauL T	Stk/Year	
Experience decay W=	Experience W/tauL W	Ton/Year	
Experience loss RA=	Cumulative production of RA/tauL RA	Ton/Year	Loss of experience for learning curve effect RA
Experience T=	INTEG(Material processing T-Experience decay T, Init experience T)	Stk	
Experience W=	INTEG(Material processing W-Experience decay W, Init Q learning W)	Ton	
FINAL TIME = 2050	Units: Year [2050,2100,10]	The final time for the simulation.	
Fraction concrete=	IF THEN ELSE(Time<HistoryEndTime,Historic fraction concrete,Future fraction concrete)	Dmnl	
Fraction demo usable T=	1	Dmnl	
Fraction new buildings tile roof=	IF THEN ELSE(Time<HistoryEndTime,Historic fraction T,Future fraction T)	Dmnl	

Fraction new concrete modular=	Initial fraction of construction modular+STEP(Step in fraction of new construction modular,Step time modular construction)	Dmnl [0,1]	Fraction new construction modular. Initially 0 (turned off)
Fraction of potential autonomous T=	0	Dmnl [0,1,0.01]	Autonomous demand as a fraction of potential demand
Fraction of potential autonomous W=	0	Dmnl [0,1,0.01]	Autonomous demand as a fraction of potential demand
Fraction of potential modules reused=	MIN(1,Relative supplier demand for concrete modules)	Dmnl	Modules reused is the minimum of what is available and what is demand. (A nonlinear funciton could also be introduced here).
Future construction starts=	7e+06	M2/Year [3e+06,9e+06,250000]	
Future fraction concrete=	0.22	Dmnl	Future assume fraction of buildings with exteriors made of concrete
Future fraction T=	0.1	Dmnl	
gamma RA=	0.1	Dmnl	Flexibility in capacity utilization
gamma T=	0.2	Dmnl	Flexibility in capacity utilization
gamma W=	0.2	Dmnl	Flexibility in capacity utilization
GPP active share RA=	IF THEN ELSE(Time<Start of GPP RA,0,GPP share RA)	Dmnl	Share of RA market that derives from activated GPP policy
GPP active share T=	IF THEN ELSE(Time<Start of GPP T,0,GPP share T)	Dmnl	Share of RA market that derives from activated GPP policy
GPP active share W=	IF THEN ELSE(Time<Start of GPP W,0,GPP share W)	Dmnl	Share of RA market that derives from activated GPP policy
GPP share RA=	0.1	Dmnl	Share of total demand that is subject to GPP
GPP share T=	0.1	Dmnl	Share of total demand that is subject to GPP
GPP share W=	0.1	Dmnl	Share of total demand that is subject to GPP
Historic buildings under construction:INTERPOLATE::=	GET XLS DATA('HISTORY.XLSX','BYGV04' ,'A' , 'E2')	M2	
Historic completed constructions:=	GET XLS DATA('HISTORY.xlsx','Data2' ,'A', 'B2')	M2/Year	
Historic Construction starts:INTERPOLATE::=	GET XLS DATA('HISTORY.xlsx','Data2' ,'A', 'B2')	M2/Year	
Historic demand T=	SMOOTHI(Demand T, tauE T,m0 T*Potential demand T)	Stk/Year	
Historic demand W=	SMOOTHI(Demand W, tauE W,0)	Ton/Year	
Historic fraction brick:INTERPOLATE::=	GET XLS DATA('HISTORY.XLSX','Data1','A', 'E2')	Dmnl	
Historic fraction concrete:INTERPOLATE::=	GET XLS DATA('HISTORY.xlsx','Data1','A','D2')	Dmnl	
Historic fraction T: INTERPOLATE::=	GET XLS DATA('HISTORY.XLSX','Data1','A','C2')	Dmnl	

Historic markup T=	SMOOTHI(Markup T, tauH T, 1)	Dmnl	
Historic markup W=	SMOOTHI(Markup W, tauH W, 1)	Dmnl	
Historic MC deployment=	SMOOTH(Redeployment MC, Time to average MC deployment)	Ton/Year	
Historical markup RA=	SMOOTHI(Markup RA, Time to adjust historical markup RA , 1)	Dmnl	Investment decisions are influenced by the long-term profitability of the sector as measured by the historical markup factor
HistoryEndTime=	2017	Year	
Indicated capacity utilization RA=	ZIDZ(Indicated production RA, Capacity RA)	Dmnl [0,2]	Indicated production relative to capacity
Indicated capacity utilization T=	ZIDZ(Indicated processing T,Processing capacity T)	Dmnl	
Indicated capacity utilization W=	ZIDZ(MIN(Wood waste generation,Desired processing W),Processing capacity W)	Dmnl	The ratio of desired processing (or available waste if it is smaller) to capacity
Indicated commercial market share T=	a T+(b T-a T)/(1+d T*EXP(-c T*WtC T*Relative attractiveness T))	Dmnl [0,1]	
Indicated commercial market share W=	a W+(b W-a W)/(1+d W*EXP(-c W*WtC W*Relative attractiveness W))	Dmnl	
Indicated commercial mkt share of RA=	aRa+(bRA-aRa)/(1+dRA*EXP(-cRa*WtC RA*Relative attractiveness of RA))	Dmnl [0,1]	Indicated market share of recycled aggregate
Indicated inventory T=	Demand T*nu T	Stk	
Indicated inventory W=	Demand W*nu W	Ton	
Indicated market share of RA=	Indicated commercial mkt share of RA*(1-GPP active share RA)+GPP active share RA	Dmnl	
Indicated market share T=	Indicated commercial market share T*(1-GPP active share T)+GPP active share T	Dmnl	
Indicated market share W=	Indicated commercial market share W*(1-GPP active share W)+GPP active share W	Dmnl	
Indicated markup factor RA=	IF THEN ELSE(epsilonS RA>100,1,Relative demand RA^(1/epsilonS RA))	Dmnl	
Indicated markup T=	IF THEN ELSE(epsilonS T>100,1,Relative demand T^(1/epsilonS T))	Dmnl	
Indicated markup W=	IF THEN ELSE(epsilonS W>100,1,Relative demand W^(1/epsilonS W))	Dmnl	Short-run markup
Indicated processing T=	MIN(Desired processing T,Material from demo roof tile)	Stk/Year	
Indicated production RA=	MIN(Concrete available for recycling,Demand RA)	Ton/Year	Indicated production is constrained by demand and by available raw materials (recycled concrete)
Init experience T=	0	Stk	Initial cumulative output for learning curve effect
Init Q learning W=	0	Ton	Initial cumulative output for learning curve effect
Initial buildings=	5.6e+08	M2	

		[500000,700000,1000]	
Initial fraction of construction modular=	0.001	Dmnl	
INITIAL TIME = 1950	Units: Year	The initial time for the simulation.	
Initial virgin material resource=	1e+09	Ton	Initial virgin material resource
Initial WtC RA=	0.1	Dmnl [0,1,0.01]	Initial WtC. Assumed to be just 10 % initially.
Initial WtC T=	0.1	Dmnl [0,1,0.01]	Initial WtC. Assumed to be just 10 % initially.
Inventory T=	INTEG(Material processing T-Sales T, Processing capacity T*nu T)	Stk	
Inventory W=	INTEG(Material processing W-Sales W, 0)	Ton	
Investment time tile capacityW=	2	Year	
K0 RA=	100	Ton/Year	Initial or reference level of recycling of RA (for learning curve and scaling effects)
K0 T=	1e+06	Stk/Year	Reference capacity for scale economy
k0 W=	500000	Ton/Year	Reference capacity for scale economy tile
Ka T=	1e+06	Stk/Year	Reference scope capacity
Ka W=	500000	Ton/Year	Reference scope capacity
kappa RA=	1	Dmnl/Year	Strength of social exposure mechanism RA
kappa T=	1	Dmnl/Year	Strength of social exposure. Dimensionless factor that is a function of how often people meet, how willing they are to change their mind in an encounter, etc.
Lambda T=	1	Dmnl	The fractional decrease in unit costs with every doubling of cumulative production. For instance, for a 30 % learning curve, lambda=0,7.
Lambda W=	1	Dmnl	The fractional decrease in unit costs with every doubling of cumulative production. For instance, for a 30 % learning curve, lambda=0,7.
LC coeff T=	LN(Lambda T)/LN(2)	Dmnl	Learning curve coefficient
LC coeff W=	LN(Lambda W)/LN(2)	Dmnl	Learning curve coefficient
Learning coefficient RA=	1	Dmnl	Coefficient of cost reduction with every doubling of experience. For instance, for a 30 % learning curve the value would be 0.7.
Learning effect T=	Relative experience T^LC coeff T	Dmnl	
Learning effect W=	Relative cumulative output W^LC coeff W	Dmnl	
Lifetime of consideration=	1e+06	Years	Decay time for familiarity (due to obsolesence or forgetting). Turned off by

			setting default to very high value.
m0 RA=	0	Dmnl [0,1,0.01]	Minimum market share of RA (see model description)
m0 T=	0.01	Dmnl	Minimum market share
m0 W=	0.01	Dmnl	Minimum market share
m1 RA=	0.9	Dmnl [0,1,0.01]	Parity market share of RA (see model description)
m1 T=	0.7	Dmnl	Market share at parity
m1 W=	0.7	Dmnl	Market share at parity
Market share T=	Sales T/Potential demand T	Dmnl	
Market share W=	Sales W/Potential demand W	Dmnl	Actual sales as a fraction of demand
Markup RA=	SMOOTHI(Indicated markup factor RA, Time to adjust markup RA, 1)	Dmnl	Markup factor: If firms perceive strong demand through stockouts etc, they may raise prices above unit cost.
Markup T=	SMOOTHI(Indicated markup T,tauM T, 1)	Dmnl	
Markup W=	SMOOTHI(Indicated markup W,tauM W, 1)	Dmnl	
Material from demo roof tile=	Switch for endogenous demo tile supply*Demolition T*Fraction demo usable T+(1-Switch for endogenous demo tile supply)*Exogenous roof tile demo supply	Stk/Year	
Material on buildings T=	INTEG(Completed construction T-Demolition T, Fraction new buildings tile roof*Roof tile per m2*Buildings)	Stk	
Material processing T=	MIN(Material from demo roof tile,Processing capacity T*Capacity utilization T)*Policy switch T	Stk/Year	
Material processing W=	Processing capacity W*Capacity utilization W	Ton/Year	
Material under construction T=	INTEG(New construction T-Completed construction T, Avg construction time*New construction T)	Stk	
Max potential recycle fraction of concrete=	0.2	Dmnl	The maximum potential fraction of concrete that could be recycled as aggregate. MiljÃ¸projekt 1667 assumes 20 %. Better demolition procedure would improve this.
MC per M2=	Concrete in buildings MC/Buildings	Ton/M2	
MC per M2 under construction=	Concrete under construction MC/Buildings under construction	Ton/M2	
MC stock adjustment time=	2	Years	
MC supplier demand=	MC supplier expected demand+MC supplier inventory correction	Ton/Year	
MC supplier expected demand=	MC supplier weight on history*Historic MC deployment+(1-MC supplier weight on history)*Potential demand for modular concrete	Ton/Year	
MC supplier inventory correction=	(MC taget stock-Stock of modules MC)/MC stock adjustment time	Ton/Year	
MC supplier weight on history=	0.5	Dmnl	

MC taget stock=	MC supplier expected demand*Required coverage MC	Ton	
mmax RA=	1	Dmnl [0,1,0.01]	Maximum market share of RA (see model description)
mmax T=	1	Dmnl	Maximum market share
mmax W=	1	Dmnl	Maximum market share
New concrete construction=	Construction starts*Fraction con-crete*Standard design concrete per M2	Ton/Year	
New concrete construction starts=	Construction starts CC+Construction starts MC	Ton/Year	Construction starts based on new con-crete
New construction T=	Construction starts*Fraction new build-ings tile roof*Roof tile per m2	Stk/Year	
nu T=	1	Year	Desired inventory coverage
nu W=	1	Year	Normal inventory coverage
P0 Initial price of VA=	190	DKK/Ton	Reference or inital price of convention-al aggregate (from virgin material). According to interview with Erik Lau-ritzen it's about 200 DKK/ton. MST Rapport 116, p. 27 botton: 10 DKK.
Pa T=	20	DKK/Stk	Reference price. See report Section 2.2.2 description of roof tiles market
Pa W=	20	DKK/Ton	Reference price. Needs to be checked and documented!
Perceived relative quality of RA=	1	Dmnl	Relative quality of recycle aggregate
pi RA=	1.5	Dmnl	Sensitivity of RA attractiveness to price
pi T=	0	Dmnl	Coefficient for price
pi W=	0	Dmnl [0,2,0.1]	Coefficient for price
Policy 2 cost reduction factor=	1	Dmnl [0,1,0.1]	Unit cost with policy relative to without
Policy switch for RA=	IF THEN ELSE (Time>= Policy year RA,1,0)	Dmnl	Switch to activate RA policy
Policy switch T=	IF THEN ELSE(Time<Policy year T,0,1)	Dmnl	
Policy switch W=	IF THEN ELSE(Time<Policy year W,0,1)	Dmnl	
Policy year RA=	2018	Year [2017,2051 ,1]	Year to activate RA policy. Starts sup-pliers building up capacity (if any)
Policy year T=	2018	Year	Year to implement policy
Policy year W=	2018	Year	Year to implement policy
Potential concrete modules available for reuse=	Processing of demolished modular con-crete*Potential fraction of modules suita-ble for reuse	Ton/Year	We assume that a there is a potential fraction of modules that are suitable for re-use. The remaining fraction (which may be zero) are either damaged or obsolete for various reasons.
Potential demand for modular concrete=	New concrete construction*Fraction new concrete modular	Ton/Year	
Potential demand T=	New construction T*Potential fraction T*(1-Switch for exogenous demand T)+Switch for exogenous demand T*Exogenous demand T	Stk/Year	
Potential demand	500000	Ton/Year	This is an exogenous variable, highly

W=			speculative
Potential fraction of modules suitable for reuse=	1	Dmnl	Maximum potential fraction of modules suitable for re-use (assuming some of them are obsolete or damaged or unusable for other reasons)
Potential fraction T=	0.75	Dmnl	Maximum potential fraction of tiles from re-use
Price effect T=	IF THEN ELSE(pi T=0,1,Relative price T^-pi T)	Dmnl	
Price effect W=	IF THEN ELSE(pi W=0,1,Relative price W^-pi W)	Dmnl	
Price of RA=	Unit cost of RA*Markup RA	DKK/Ton	Price of recycle aggregate
Price of VA=	P0 Initial price of VA*Effect of availability on price of VA	DKK/Ton	Price of conventional aggregate
Price T=	Unit cost T*Markup T	DKK/Stk	
Price W=	Unit cost W*Markup W	DKK/Ton	
Processing capacity T=	INTEG(Capacity investments T-Capacity depreciation T, Target capacity T)	Stk/Year	
Processing capacity W=	INTEG(Capacity investments W-Capacity depreciation W, Target capacity W)	Ton/Year	
Processing of conv demo concrete=	Demolished concrete CC/Avg processing time of demo concrete	Ton/Year	
Processing of demolished modular concrete=	Demolished concrete MC/Avg processing time of demo concrete	Ton/Year	
Production RA=	Policy switch for RA*Capacity RA*Capacity utilization RA	Ton/Year	Actual concrete recycled is constrained by the demand for recycled material, the available material for recycling, and the processing capacity of the recycling sector.
Q T=	1	Dmnl	Perceived quality
Q W=	1	Dmnl	Perceived quality
QA T=	1	Dmnl	Quality of existing alternative
QA W=	1	Dmnl	Quality of existing alternative
Quality effect T=	IF THEN ELSE (theta T = 0,1,Relative quality T^theta T)	Dmnl	Effect of quality on attractiveness
Quality effect W=	IF THEN ELSE (theta W = 0,1,Relative quality W^theta W)	Dmnl	Effect of quality on attractiveness
RA market share=	Production RA/Demand for aggregate	Dmnl	
RA supplier weight on history=	1	Dmnl	
Recycling=	Recycling CC+Recycling MC	Ton/Year	
Recycling CC=	Concrete available for recycling CC*Production RA/Concrete available for recycling	Ton/Year	Assumed to be apportioned the same way between conventional and modular concrete
Recycling MC=	Concrete available for recycling MC*Production RA/Concrete available for recycling	Ton/Year	Assumed to be apportioned the same way between conventional and modular concrete
Redeployment MC=	Potential demand for modular concrete*Effect of availability on modular concrete	Ton/Year	
Reference cumulati-	100	Ton	Reference cumulative production for

ve production RA=			learning purposes
Reference unit cost of RA=	150	DKK/Ton	Ininitial processing cost of RA. MiljÃ¸projekt 1667 p. 27: 150 DKK estimate. Includes transportation costs.
Reference unit cost T=	20	DKK/Stk	
Reference unit cost W=	20	DKK/Ton	
Relative attractiveness of RA=	Effect of price RA attractiveness*Effect of quality on RA attractiveness	Dmnl	Relative attractiveness of recycled aggregate
Relative attractiveness T=	Price effect T*Scope effect T*Quality effect T	Dmnl	Relative attractiveness
Relative attractiveness W=	Price effect W*Scope effect W*Quality effect W	Dmnl	
Relative availability of modular concrete=	Stock of modules MC/(Potential demand for modular concrete*Required coverage MC)	Dmnl	
Relative cumulative output W=	MAX(1,Experience W/E0 W)	Dmnl	
Relative demand RA=	ZIDZ(Demand RA,Capacity RA)	Dmnl	Demand for RA relative to capacity
Relative demand T=	Demand T/Processing capacity T	Dmnl	
Relative demand W=	ZIDZ(Demand W,Processing capacity W)	Dmnl	The ratio of indicated demand to capacity
Relative experience T=	MAX(1,Experience T/E0 T)	Dmnl	
Relative inventory T=	ZIDZ(Inventory T,Indicated inventory T)	Dmnl	
Relative price of recycled aggregate=	Price of RA/Price of VA	Dmnl	Relative price of recycle aggregate
Relative price T=	Price T/Pa T	Dmnl	
Relative price W=	Price W/Pa W	Dmnl	
Relative quality T=	Q T/QA T	Dmnl	Relative quality
Relative quality W=	Q W/QA W	Dmnl	Relative quality
Relative scale T=	Processing capacity T/K0 T	Dmnl	
Relative scale W=	Processing capacity W/k0 W	Dmnl	
Relative scope T=	Processing capacity T/Ka T	Dmnl	
Relative scope W=	Processing capacity W/Ka W	Dmnl	
Relative supplier demand for concrete modules=	MC supplier demand/Potential concrete modules available for reuse	Dmnl	
Required coverage MC=	5	Years	Parameter indicating the required inventory coverage to assure sufficient availability and variety of concrete modules for new construction.
Reuse MC=	Potential concrete modules available for reuse*Fraction of potential modules reused	Ton/Year	There is a potential total supply of modules for re-use, but some may not be re-used if module suppliers do not have the capacity or incentive to do so.
rho T=	0	Dmnl [0,2,0.01]	Coefficient for scope economy
rho W=	0	Dmnl	Coefficient for scope economy

Roof tile per m2=	10	Stk/M2	Estimate from historical data. About 15 mio. tiles produced per year. Total new construction of about 5-6 mio. m2, about 10 % of which is with tile roof. But 30 tiles per m2 seems high, so we set at 10 tiles per m2.
Roof tile per m2 under construction=	Material under construction T/Buildings under construction	Stk/M2	
Roof tiles per m2 buildings=	Material on buildings T/Buildings	Stk/M2	
S W=	ZIDZ(Inventory W,Indicated inventory W)	Dmnl	Relative availability (stock)
Sales T=	Demand T*Eff of inventory on sales T*Policy switch T	Stk/Year	
Sales W=	Demand W*Eff of inventory on sales W	Ton/Year	
SAVEPER =	TIME STEP	Year [0,?]	The frequency with which output is stored.
Scale economy effect T=	IF THEN ELSE(Relative scale T=0,1,Relative scale T^-alpha T)	Dmnl	
Scale economy effect W=	IF THEN ELSE(Relative scale W=0,1,Relative scale W^-alpha W)	Dmnl	
Scope effect T=	IF THEN ELSE (rho T=0,1,Relative scope T^rho T)	Dmnl	
Scope effect W=	IF THEN ELSE (rho W=0,1,Relative scope W^rho W)	Dmnl	
Sensitivity of RA to quality=	0.5	Dmnl	Sensitivity of attractiveness to quality
Sigma MC Sensitivity of modular demand to availability=	0.1	Dmnl	Measures how sensitive the choice of modular concrete is to availability of modular concrete.
sigma T=	0.2	Dmnl	Sensitivity of sales to availability (inventory)
sigma W=	0.2	Dmnl	Sensitivity of sales to availability (inventory)
Size of marketing campaign RA=	0	Dmnl/Year [0,?]	
Size of marketing campaign T=	0	Dmnl/Year [0,1,0.01]	Size of marketing campaign.
Standard design concrete per M2=	2.5	Ton/M2 [1,3,0.1]	Parameter derived by comparing to history (estimate)
Start of GPP RA=	1e+09	Year [0,1,1]	Year to initiate GPP policy
Start of GPP T=	2050	Year [2010,2050,1]	Year to activate GPP policy
Start of GPP W=	1e+09	Year [2010,2050,1]	Year to initiate GPP policy
Start of marketing campaign T=	2018	Year	
Start time of marketing campaign RA=	2018	Year	
Step in fraction of new construction modular=	0	Dmnl	

Step time modular construction=	100	Year	
Stock adjustment T=	(Desired stock T-Inventory T)/Time to adjust stock for tiles	Stk/Year	
Stock adjustment W=	(Desired stock W-Inventory W)/Time to adjust stock W	Ton/Year	
Stock of modules MC=	INTEG(Reuse MC-Redeployment MC, Required coverage MC*Potential demand for modular concrete)	Ton	Initially equal to the reference inventory required for full utilization of modular concrete
Strength of scarcity effect=	0.1	Dmnl	Measures the strength of the scarcity effect when virgin resources are depleted
Switch for endogenous demo tile supply=	0	Dmnl [0,1,1]	Set to 0 for exogenous inflow of tiles and 1 for calculated inflow from aging structure of buildings.
Switch for exogenous demand T=	1	Dmnl [0,1,1]	Set to 0 for endogenous roof tile demand, 1 for exogenous
Target capacity RA=	MIN(Concrete available for recycling,Expected future demand RA)*Effect of markup on target capacity RA	Ton/Year	Desired capacity is a combination of expected (target) production and a factor from profitability.
Target capacity T=	MIN(Material from demo roof tile,Expected future demand T)*Effect of markup on capacity T	Stk/Year	
Target capacity W=	MIN(Wood waste generation,Expected future demand W)*Effect of markup on output W	Ton/Year	
tauC RA=	5	Years	Average lifetime of capacity
tauC T=	10	Year	Average lifetime of capacity
tauC W=	10	Year	Average lifetime of capacity.
tauE RA=	1	Years	Time to adjust expected future demand
tauE T=	2	Year	Time to average historic demand
tauE W=	2	Year	Time to average historic demand
tauH T=	1	Year	Time to average historical markup
tauH W=	1	Year	Time to average historic markup
tauK RA=	2	Years	Capacity investment time
tauK T=	2	Year	Capacity investment time
tauL RA=	10	Years	Lifetime of relevant experience
tauL T=	10	Year	Avg lifetime of experience
tauL W=	10	Year	Average lifetime of experience
tauM T=	0.25	Year	Time to adjust markup
tauM W=	0.25	Year	Time to adjust markup
theta T=	0	Dmnl [0,2,0.1]	Sensitivity of demand to quality
theta W=	0	Dmnl	Sensitivity of demand to quality
TIME STEP = 0.015625	Units: Year [0,?]	The time step for the simulation.	
Time to adjust historical markup RA=	2	Years	Time to adjust long-term expectations of profitability.
Time to adjust markup RA=	0.25	Years	

Time to adjust stock for tiles=	1	Year	
Time to adjust stock W=	1	Year	
Time to average MC deployment=	2	Years	
Traditional disposal=	Traditional disposal CC+Traditional disposal MC	Ton/Year	
Traditional disposal CC=	Processing of conv demo concrete-Recycling CC	Ton/Year	Whatever is not recycled is disposed of traditionally
Traditional disposal MC=	Processing of demolished modular concrete-Recycling MC-Reuse MC	Ton/Year	Traditional disposal assumed to be the remainder after recycling and re-use
Unit cost of RA=	Reference unit cost of RA*Effect of scale economy on cost of RA*Effect of learning on cost of RA*(1-Policy switch for RA+Policy switch for RA*Policy 2 cost reduction factor)	DKK/Ton	Reflects all costs except the opportunity cost of the alternative use of concrete in traditional applications
Unit cost T=	Reference unit cost T*Scale economy effect T*Learning effect T*(1-Policy switch T+Policy switch T*Policy 2 cost reduction factor)	DKK/Stk	
Unit cost W=	Reference unit cost W*Scale economy effect W*Learning effect W*(1-Policy switch W+Policy switch W*Policy 2 cost reduction factor)	DKK/Ton	
Use of virgin aggregate=	Demand for aggregate*(1-RA market share)	Ton/Year	
Virgin material resource=	INTEG(-Use of virgin aggregate, Initial virgin material resource)	Ton	Virgin material resource
wH T=	1	Dmnl	Weight on historic demand (versus autonomous). Set to 1 for only history, 0 for only autonomous.
wH W=	1	Dmnl	Weight on history
Wood waste generation=	500000	Ton/Year	Assume it is 107.000 recycled today at Kronospan plus 320.000 plus possibly from furniture, plus some more....
WtC RA=	INTEG(Effect of marketing on WtC RA+Effect of social exposure on WtC RA-Decay of WtC RA, Initial WtC RA)	Dmnl [0,1,0.01]	Willingness to consider RA for concrete
WtC T=	INTEG(Effect of marketing on WtC T+Effect of social exposure on WtC T-Decay of WtC T, Initial WtC T)	Dmnl [0,1,0.01]	Willingness to consider used tiles
WtC W=	1	Dmnl	Willingness to consider. Is considered constant here.

Appendix 3. Model runs (parameter changes)

Base	alpha W = 0.5 pi W = 0.5 rho T = 0.5
Base2	Initial WtC RA = 0.2 Initial WtC T = 0.2
Base3	Initial WtC T = 1
Base4	Initial WtC T = 1 rho T = 0.5
Base5	alpha W = 0.5 pi W = 0.5
Run01	kappa RA = 2 kappa T = 2 rho T = 0.5 Size of marketing campaign RA = 0.1 Size of marketing campaign T = 0.1
Run02	kappa RA = 2 kappa T = 2 Q T = 2 rho T = 0.5 Size of marketing campaign RA = 0.1 Size of marketing campaign T = 0.1 theta T = 1
Run03	Ka T = 500000 kappa RA = 2 kappa T = 2 rho T = 0.5 rho W = 0.5 Size of marketing campaign RA = 0.1 Size of marketing campaign T = 0.1
Run04	Ka T = 500000 kappa T = 2 Q T = 2 rho T = 0.5 Size of marketing campaign T = 0.1 theta T = 1
Run05	Ka T = 500000 kappa T = 2 rho T = 0.5 Size of marketing campaign T = 0.1 theta T = 1
Run06	alpha W = 0.5 pi W = 0.5 rho T = 0.5 Start of GPP RA = 2020 Start of GPP T = 2020 Start of GPP W = 2020

Appendix 4. Interview transcripts

1. Erik Lauritzen

Technical Barriers

General

Insufficient data

The european data on C&DW is insufficient. The registration is conducted differently in every country. The Danish 'Affaldsdatasystemet' only registers waste when it is delivered to waste incineration or another treatment plant. Regarding wood it is okay because it is mainly transported to incineration or modtageanlæg but quite a big share of the concrete waste is directly sold as road base material and hence is not registered at any plant.

Erik believes the quantity of concrete waste is more likely to be 3/4/5 mill. Tons. Than the registered 1 mill. Tons.

Lack of knowledge

There is not a lot of coherent knowledge on the field. We still refer to literature from the 90's. There is a lack of a substantial overview of all literature on the subject.

China is ahead in the development of new concrete technology but still they are repeating what we wrote 25 years ago.

Solutions:

- Gather all information
- Make new demonstration projects which also focuses on economy

Lack of commitment from advisors

Consultants does not have the knowledge to advise on recycling and they do not want the trouble. It takes time and money to do things differently and there is too much trouble in making special standards and convincing the owners.

Solution: Stakeholder commitment is important

Lack of general solutions

There is a certain amount of 'waste architects' (Lendager etc.) but they make unique solutions that cannot be transferred to general building culture

Lack of guarantee on recycled materials

If the materials (concrete and tiles) meets the standards of new products, then you should be satisfied and take responsibility

Difficult with roof tiles as they come in different sizes but the key issue is to know the source and the quality

CE-marking of tiles might make it easier to sell but the different sizes etc. makes it difficult to harmonize the standard

Technical possibilities

High quality

The quality of old materials is often better. Especially wood which also benefits from the possibility of being able to be cut into smaller pieces. E.g. construction timber being cut in to window frames and cabinets.

Older roof tiles are also of better quality but does not have the same possibility of being made in to other products.
Floor planks can be planed down several times. Erik thinks there is a market if they are taken out, restored and matched.
Security of supply

- The demolishers cannot guarantee that they have a certain material at a certain time
- The waste streams are not controlled hence small amounts and uneven fractions
  - Solution: strategic regional planning. I am working on a project with Danske Maskinstationer og Entreprenører DM&E. Their members are150 very small demolition contractors. If they organize all their waste in the same fractions and store it the same places, they can secure a better security of supply

Security of sales

- If you do not have a buyer you have to store the materials. This costs in transportation and storage and makes it more difficult to sell. E.g. Unicef's Administration building on Marmormolen:
- A lot of high valuable beams (limtræ) was incinerated because the demolition contractor claimed it was not possible to sort out

The keyword on recycling is matching.
You need to know where the materials are going before demolition. The best solution is to know the buyer before demolition.
In a new report for MST we are trying to involve the owners at a very early stage, so the demolition phase can be planned better. We want the owner to make a pre-demolition-audit to map and match the resources at an early stage.

Wood

TI has proven the risk of Tertiary polluted wood. It can be removed but costs money

Roof tiles
Fragile during the demolishing phase
Solution: Erik has not done the calculations but believes the reused tiles can be sold cheaper than new ones despite the costs of selective demolishing.

Concrete
There is already a functioning market
- The road base material from recycled concrete is better than road base material of gravel.

Not all the concrete waste is the required quality
- -maybe 20 %

Uncertain whether recycled concrete needs for cement
- According to Erik: 'Fake news' from the concrete industry

Elements:
- No byers
- Difficult to separate because the 'straps' for carrying is cut of once in place

- Maybe smaller bricks but elements are too big

Economic Barriers

Lack of time for demolition

The demolition phase is longer when doing selective demotion and it often needs to be done by hand.
Solutions:
Subsidies or taxes on raw materials
"Hvis man vi starte et marked for genbrugt træ bliver de nødt til at have et incitament i begyndelsen (støtte) men når forretningen kører tror jeg ikke støtte er nødvendigt, de skal bare have nogle startpenge"

The building owner is not willing to pay extra for recycled materials.

- Especially not public owners as they are dealing with tax payers money.
- Erik finds it difficult to convince the Copenhagen Municipality of using recycled materials.

The owner does not know about the economic possibilities

E.g. Katrinedals Skole: Gamle Mursten payed the demolition contractor 50 øre/brick. This income should benefit the owner.
The same should be applicable for wood materials
Solution:
The owner will not lose money on selective demolition.
"Mit løfte til ARC er at de sparer 100 kr på tons grus i den nye beton sammenlignet med konventionel ready-mixed concrete."

Regulatory Barriers

General

Lack of standards for recycled materials

Concrete
According to the standards written in EN 206 standard the use of crushed concrete in new concrete is possible in smaller amounts (20-30%).
Wood
There are some technical specifications that needs to be overcome to enhance recycled wood.

- Gamle Mursten is getting an ETA-certification but wood and other materials do not have that (e.g. wood).
- Old wood materials do not have certification, but it should be treated as so.
- When building the recycled houses in the 90's we had trouble convincing ´the wood people´ that you can actually have a norm for holey wood.

CO2 as a success criterium

It helps to start thinking primarily the CO2 reductions from specific solutions. The transport branch has no restrictions as CO2 is not a success criterion for any alternative. The production of roof tiles and wood is not so CO2-demanding, but transport is.

2. Preben Nielsen (BYGMA)

Technical barriers

General

Lack of guarantee
The production company is responsible for the quality of a new product and gives a guarantee for a certain amount of years. But this guarantee disappears when the product is taken down and used somewhere else and who will take the responsibility then?
Documentation on both statics and traceability are important.
Needs new testing from a lab which is an extra cost
Lack of security of supply
Industrialized construction requires a tight security of supply. The materials need to be delivered at a very specific time and in a specific quality.
BYGMA don't see reused materials as their market (like Genbyg Skive) but they believe they can compete on security of supply.
We have traded old bricks, but demand and supply must be matched it does not make sense to storage. The chances of having the right amount and quality in stock are too small.

Wood
From windows
Nobody reuses old frames from new windows. It is too expensive. But windows are being replaced to a high extend because of demands on sound- and heat insulation. Also, Bygningsreglementet 2020 pushes the requirements.
Floor planks
Newer planks are often plywood topped with finér which means it can only be sanded 2-3 times. Abrasion and nail holes effects the quality.
Older floors are of better quality (Juncers) and can last for 100 years

Roof tiles
Older tiles of clay are often applied with mortar which is difficult to remove from the fragile tiles.
Important they have the same size (unlike bricks which can be adjusted with more/less mortar)
Glazed tiles have a longer life expectancy because they are not exposed to abrasion.

Economic barriers

If costumers are willing to pay more for recycled products it is because it is bigger constructions and demanded by the architect or owner.
We do not sell a lot of certified wood even though it is a legal requirement to use in new public constructions. If the contractor needs to fin e.g. 2 million kr. Extra. The sustainable products are dropped.

3. Jeanett Vikkelsøe (Marius Pedersen)

Sources
Marius Pedersen deals with recycling, so they can provide no information on re-use of construction wood.

They receive wood from municipalities, recycling stations, construction and demolition companies, contractors and private companies. The wood waste is delivered to the Marius Pedersen facilities, checked and then mixed together, regardless of the source, according to predefined wood qualities (A1, A2, A4).

Products
Clients: Biomass and energy plants, chipboard makers

There are four types of wood waste:

A1. Typical residual wood from furniture industry, not from demolition, free from contaminants such as nails
A2. Wood chips
A3. Wood chips (uncertain)
A4. Impregnated wood suitable for energy recovery

Marius ensures that wood waste is sorted accordingly. If it is not sorted already when received, Marius does so and the costs are covered through the received gate fee.
Demolition companies are good at sorting, they know well the fractions they should sort into. They are also aware that it costs more to get rid of unsorted wood waste.
If they are forced to sort better (than the law commands now) there should be economic incentives. Either there should be penalties for not doing it or a market for clean wood waste should be developed.

Quantities
Maris receives annually 200,000 t +/- 20,000 in Denmark. Around a third of that goes to energy recovery and the rest to the chipboard sector.
Marius does not deal with reuse. This would require large storage areas for the different wood applications (doors, floors, planks). Marius has not made any market research on this.

Market
There is a balance between supply and demand on the amounts Marius buys and sells right now. They use the European market. New plants are built in Germany and Poland. The largest distance for Danish wood waste is the Berlin area, but if the market commands it, longer distances are possible.
The Marius clients pay various prices according to the wood waste quality (size, moisture level etc.). As long as there is demand for wood chips and fees for incineration, sorting of wood waste will be good business.

Regulations
Treatment of waste wood into chipboards requires a quality material. Quality requirements for raw materials exist and they are used in order , e.g. to prove that there is no arsenic in the wood that goes into chipboards. A barrier for Marius is the Waste Shipment Regulation that demands notification for every shipment which is very time consuming.

Documentation
Marius uses laboratories to test the collected wood in terms of hazardous substances.

Quality
The clients have specific demands for the wood they receive, for example for chipboard production in terms of size. Wood cannot, for example, be stored for six months as it decays. The same situation happens for energy recovery.

Security of supply
Security of supply is very important for delivery of raw materials. Marius has many different sources and the quantities they can deliver vary with +/- 20% every month or year, because of won/lost contracts. This requires a flexible storage and production system.
The environmental permit determines how much Marius can have in storage, not for how long.

4. Thomas Uhd (Dansk Beton)

<u>Technical challenges</u>

Standards
Concrete with recycled content should live up to the requirements of conventional concrete. The building sector is often conservative in terms of materials' choice but is also required.

Knowledge
- What should the recipe be, how can we make concrete recycling work?
- In the Netherlands, they clean the heavy concrete fraction and use concrete as road sub-base. It makes sense there due to lack of natural resources, but this is not a problem in Denmark
- Elasticity and increased supply of concrete

Practicalities
If a company wants to supply aggregates other than the conventional ones, this requires more silos, which cost money. Moreover, there is a risk that concrete starts to react and collude in the silos, so there should be vibrators there too.

Raw materials

Market needs
Copenhagen Economics predicts a shortage within 14-43 years, but only with respect to existing mining sites. So, if more sites are created, there might be no shortage. But in the capital region, we can see that there are some shortage issues. If someone can produce quality aggregates, these will be used, as the alternative is to transport them from far away and that is expensive. Transport costs are a larger part of the final aggregates price than extraction. Moreover, there might be some political challenges for virgin resources, that secondary materials might overcome.
Derudover kan der være nogle politiske udfordringer for primære ressourcer, som kan komme de sekundære til gode. For example, harbour erosions due to mining, "not in my back yard" mentality, increase taxes on raw materials etc.

Replacement potential
By using waste concrete in new concrete, the aim should be to replace high quality aggregates not low quality ones. In the capital region, high quality aggregates are in shortage and they become fewer and fewer. I don't know if we can find filling material in the capital region (current application of concrete waste). For that there is a lower demand, which is reflected in the price. Filling material is more abundant in general than quality aggregates.
The bottom line is that if we can use waste concrete to produce good quality aggregates, this is a good business case, especially if we have to transport natural aggregates from Jutland.

Product

The growth of the building stock is around 1% per year, so it will be a while until a large part of the buildings are made based on the design-for-disassembly concept. Therefore, concrete waste will be abundant for many more years. It can primarily be used in ready mix concrete, such as the one made in Amager, Avedøre and Hillerød.
Any application needs to have a certain scale and quality, so that it can be delivered to a plant and processed, so that it can have a CE label on and that it passes the controls on hazardous materials.
On-site recycling depends on many factors, such as quality, timing, etc. and demands continuous on site testing. This is rather expensive. In the Pelican example, the concrete production was controlled manually, but the big concrete producers do this based on computer-controlled recipes.

Costs

There is not that much information available on costs for concrete processing. The knowledge we have from the Netherlands is based on cleaning of the aggregates and giving a discount to the building owner so that recycled concrete can fetch higher prices – 50 Euros more per cubic meter. In order to estimate the true cost difference between natural aggregates and crushed concrete, we need to focus on:

- Selective demolition
- Source separation
- More containers for more demolition fractions
- Processing to CE-labelling quality
- Extra transport

In any case, there are a few things that should be improved and we know that detailed selective demolition and proper materials separation is difficult. RGS Nordic has initiated a project on crushed concrete with high uncertainty on if this is a business case.

Regulations

No barriers in terms of regulations, except perhaps that regulations could support recycling better.

Taxes vs. Subsidies
We should be careful not to skew the market with regulations:
Higher raw material taxes might mean that further development of aggregates in order to reach the highest possible quality might be hindered. For example, maybe people start to build with plaster as this is easily recycled. Therefore, I believe a subsidies model is better, focus on the carrot, not the stick.

LCA and environmental declarations
Efforts on voluntary sustainability classes could be a preparatory step for changes in the building regulation and could further develop recycling. The focus should be on EPDs and LCAs that bring data on the table. It is not the case now, but I can imagine LCA to be a requirement after 2025.

5. Søren Nielsen (Vandkunst Arkitekter)

Barriers

Uncertainty and responsibility
If there is any uncertainty in regards of safety or economy, there is no demand. This is the case for recycled concrete.

- Public owners are among the most conservative costumers because of their predominant focus on regulation and economy.
- Boligselskaber are more liable to try new things. They have no investors, 'non-profit' so to speak.
- Advisors initiative and advisor's responsibility. Hence, they are responsible if anything happens.
  Unless they can have the owners take the responsibility but that never happens because the person who acts for the owner (company) does not want to lose his job. Architects have an insurance, but as a client advisor insurance claims are not good for your company.
- The architects could make the decisions based on extra testing, but this is expensive.
- If the development of technology makes testing cheaper (e.g. if you don't need an advising engineer to perform the testing) it might be possible to overcome this barrier.

- Some technological solutions are already developed but too expensive for small streams. If someone could gather all the small streams of waste it might be profitable, but who should take the risk of doing so?

Security of supply

- but the architects also need to be more flexible on delivery. The quantities of concrete are quite large but in regards of other materials the architects must be more flexible towards the consignment and 'look' especially in the transition phase.
- The regulation concerning public tenders can become a barrier for the security of supply**.**
  Public owners are required to make tenders for both contractors and materials which means they cannot simply reserve materials from constructions ready for demolition.
- The less flexible supply of recycled materials can cause problems for private owners as the construction is often financed in smaller steps.

Higher costs

Building owners are not willing to pay more for recycled products

- If recycled materials were more valued in certification systems such as DGNB a few owners might be willing to pay a bit more, but not a lot of owners are aiming for optional certification of buildings (like DGNB etc.).

Wood

- Windows: Possible to reuse the frames, but expensive. Only happens in preserved buildings. The extended use of processed wood makes a big impact on the costs.
- Floors: Less hazardous substances. Genbyg is trying to have Juncer take back 80.000 m3 of high quality floors for processing and resale but only possible because of the large quantities.
  Also, the German market buys reused parquet.
  This was written into the tender document; there had to be time for salvage of the wooden floors and a collaboration with a byer (in this case genbyg).
  The demolition costs a bit more, but the floors are saved.
- Again, who takes the risk and kickstart the market? Genbyg is doing some of the work but not all of it.

Roof tiles

- Mostly reused at a very small scale.
- Uncertainty of the quality when reused for roofs because of the importance of watertight roofs affects the entire construction.

- Possible case in Musicon, Roskilde where Vandkunsten wants to reuse roof tiles as facing on genbrugsstationer.
- Extra costs connected to demolition, but a small amount; two days work for two persons.
  Possibilities in cases of lack of security of supply: Flexible planning – make it possible to use different kinds (e.g. 20 different types) and if its not possible to wake the entire facing in one type; makes stripes or the like.

Believes this will only happen (in large scale) in case of severe resource scarcity

Establishing effective markets for secondary building materials

The overall objective of the project is to frame the development towards an effective market for secondary products obtained through reuse and recycling in a large scale. The focus is on the conditions and requirements necessary for establishing an effective market for secondary products that can also help introduce new, innovative business models related to the processing and recycling of construction and demolition waste.

The Partnership on sustainable construction and waste prevention has selected concrete, wood and roof tiles wastes for detailed analysis as they are considered to have a potential for recycling and re-use as well as for developing new secondary products from them.

For each material, the current market conditions and functioning was investigated and barriers where identified. The most important barriers seem to be the following: current market inertia, the lack of documentation and guarantees, insecurity of supply as wells as costs associated with waste processing and – in some cases - the presence of hazardous substances in the waste.

In order to overcome the identified barriers and establish a truly effective waste market an idea catalogue suggests: match-making platforms that help match supply and demand, compilation of standards and documentation, demonstration projects focusing on costs and a more strategic use of green public procurement are considered the most effective tools.

These results are supported by the development of a dedicated economic model. The model simulations of the different initiatives show how market parameters such as price and security of supply are affected.

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