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*Mauricio Cote*

# Circularity of carbon-based material systems in the German anthroposphere

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# Circularity of carbon-based material systems in the German anthroposphere

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Referent: Prof. Dr. rer. nat. Liselotte Schebek
Korreferenten: Univ. Prof. Dipl.-Ing. Dr. techn. Helmut Rechberger
Prof. Dr.-Ing. Ulrich Knaack

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Herstellung: Lasertype GmbH, Holzhofallee 19
64295 Darmstadt

Vertrieb: Institut IWAR
TU Darmstadt
Franziska-Braun-Straße 7
64287 Darmstadt
Telefon: 06151 / 16 20801
Telefax: 06151 / 16 20822

**Zum Autor:**

Mauricio Cote wurde 1982 in Bogotá, Kolumbien geboren. Nach seiner schulischen Ausbildung nahm er das Studium des Chemieingenieurwesens an der Universidad de los Andes in Bogotá auf, welches er 2006 als Bachelor of Science abschloss. In seiner veröffentlichten Bachelorarbeit beschäftigte er sich mit der Entwicklung von antistatischen Schutzfilmen von Polyethylen-Polyanilin (LDPE-PANI). Von 2007 bis 2009 arbeitete er bei Holcim (Colombia) S.A. als Betriebsingenieur. 2009 begann er das Studium Renewable Energy Management an der Universität Freiburg und erlangte 2011 den Master of Science. 2012 trat er eine Stelle als wissenschaftlicher Mitarbeiter (Doktorand) am Karlsruher Institut für Technologie an. Dort befasste sich Herr Cote als externer Doktorand der TU Darmstadt am Institut IWAR im Fachgebiet Stoffstrommanagement und Ressourcenwirtschaft mit dem Thema „Kohlenstoffmanagement“, um anthropogene Kohlenstoffflüsse und Bestände zu modellieren. Die Ergebnisse der Untersuchung bilden die Grundlage der vorliegenden Dissertation.

**Zum Inhalt:**

Die Anthroposphäre ist das vom Menschen geschaffene System, in welchem Materialflüsse und -bestandsveränderungen durch sozioökonomische, bio-chemische und kulturelle Aktivitäten bewusst erzeugt werden. Diese Aktivitäten enthalten energetische und stoffliche Prozesse und wirken sich über die Nachfrage nach Ressourcen sowie durch Prozesse der Abfallwirtschaft auf die Umwelt aus. Somit sind Anthropogene Materialsysteme (AMS) zu einem grundlegenden Forschungsgegenstand geworden. Die Verwertung von kohlenstoff-basierten Materialien wie Holz, Papier und Plastik verursachen C-Emissionen, welche den Klimawandel beeinflussen. Allerdings können anthropogene Kohlenstoffbestände durch Transformierung in sekundäre Rohstoffe zur Bewältigung von C-Emissionen beitragen. In Deutschland werden gegenwärtig über 90 Mio.t C-basierte Rohstoffe pro Jahr nachgefragt. Mit dem Ziel, Kohlenstoff in der Volkswirtschaft effizient zu nutzen, wurde die Strategie der Zirkularität entwickelt. Nach der Methode der Stoffstromanalyse wurde ein gesamtwirtschaftliches dynamisches Materialfluss- und Bestandsmodell erarbeitet. Es zeigte sich in den Analysen, dass Holz vornehmlich im Bestand der deutschen Anthroposphäre zu finden ist. Bei Papier ist bis zum Jahr 2055 mit einem konstanten Zuflluss zum Bestand zu rechnen. Dahingegen kann trotz einer abnehmenden Bevölkerung eine Verdopplung der Nachfrage nach Kunststoffen in den nächsten 40 Jahren erwartet werden. Aufbauend auf den Szenarioergebnissen wurden vier Kreislaufindikatoren entwickelt. Eine Verringerung von C-Emissionen ist möglich, wenn Recycling und umweltfreundliches Konsumverhalten richtig kombiniert werden. Die Untersuchung hebt die Relevanz von Kohlenstoff in AMS hervor, um Wissen für den Wandel hin zu nachhaltigen kohlenstoffarmen Gesellschaften voranzutreiben.

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## Contents

# Zusammenfassung

Die Anthroposphäre ist das vom Menschen geschaffene System, in welchem Stoffströme und Bestandsveränderungen durch wirtschaftliche, soziale, biologische und kulturelle Aktivitäten bewusst erzeugt werden, um komplexe sozioökonomische Bedürfnisse, Beziehungen und Strukturen zu entsprechen. Diese Aktivitäten unterhalten energetische und nichtenergetische (bzw. materielle) dynamische Prozesse aus der Perspektive des Sozioökonomischen Metabolismus (SEM). Gleichwohl üben die Nachfrage nach immer knapper werdenden Ressourcen und Rohstoffen sowie die Prozesse der Abfallwirtschaft Druck auf die Umwelt aus. Somit sind Anthropogene Materialsysteme (AMS) zu einem grundlegenden Forschungsgegenstand geworden, um die Auswirkungen der Materialflüsse und Bestände innerhalb der Volkswirtschaften zu verstehen, die sich im Übergang befinden von einer traditionellen biogene-Ressourcen-basierten stoffflussabhängigen Betriebskapazität hin, zu einem starken anthropogene-Ressourcen-basierten bestandsabhängigen Bedarf.

Die essenzielle Komponente des gegenwärtigen globalen *status quo* der Energie- und Materialaktivitäten, sowohl auf biogener als auch auf anthropogener Ebene, ist Kohlenstoff (carbon, C). Die Verwendung von Kohlenstoff in Aktivitäten, die mit anthropogener Energie verbunden sind, wie etwa Transport, Elektrizitätserzeugung und Heizung, u.a., bringt Kohlenstoffemissionen mit sich, welche den menschengemachten Klimawandel fördern. Jedoch können Kohlenstoffemissionen potentiell auch aus Kohlenstoff-basierten Materialien (carbon-based materials, CBM) wie zum Beispiel Holz, Papier und Plastik freigesetzt werden, mit zusätzlichen Effekten für die globalen Ökosysteme. Auf diese Weise helfen die aus Konsum- und Kapitalgütern aufgebauten anthropogenen Kohlenstoffbestände bei der Bewältigung von weiteren Kohlenstoffemissionen, was ihre Wichtigkeit als zentrale Säulen des SEM in der Entwicklung von Managementsystemen für nachhaltige Ressourcen und Kohlenstoff illustriert. Mit anderen Worten, anthropogene Kohlenstoffbestände können zu Sekundären Rohstoffen (secondary raw materials, SRM) werden, welche den Druck auf Primärressourcen, Abfallvolumen in ihrer Post-Konsumphase und Kohlenstoff-bezogenen Emissionen reduzieren.

Die erstaunlich hohe globale Produktion, Konsumierung und Handel von Kohlenstoff-basierten Ressourcen wie Biomasse und Rohöl steigert den Materialdurchsatz von Kohlenstoff in der Anthroposphäre dramatisch. In Deutschland beispielsweise werden seit 1950 steigende Pro-Kopf-Verbrauchs- und Produktionsraten in Dienstleistungsbereichen wie Verpackung, Transport, Kommunikation und Bau, u.a., beobachtet. Gegenwärtig werden über 90 Millionen Tonnen (Mio.t) Kohlenstoff-basierte Rohstoffen pro Jahr nachgefragt, da auf den Märkten permanent neue Produkte und Anwendungen eingeführt werden. Der deutsche Pro-Kopf-Verbrauch von CBM ist einer der höchsten der Welt, mit einer erwarteten durchschnittlichen Steigerung von 1,3% pro Jahr bis 2030. Deutschland hat den weltweit viertgrößten Papiermarkt und die höchsten europäischen Verbrauchsraten von Papier, Bauholz und Plastik. Die Papierindustrie ist kontinuierlich und schnell gewachsen (ungefähr 1,8% jährlich seit 1985), wodurch sie in 2014 eine Produktion von 23,1 Mio.t erreichte. Die Holzindustrie ist seit 1950 beinahe um das Dreifache gewachsen und erreichte in 2013 einen Verbrauchsumfang von 72,5 Mio.$m^3$, darunter 65% für stoffliche Nutzung. Die Plastikindustrie hat fast 19,8 Mio.t Harz für die Standard- und technisch anspruchsvolle Polymerherstellung produziert und ist somit dreimal so schnell gewachsen wie die Papierindustrie. Infolgedessen werden in großem Umfang genutzte anthropogene Kohlenstoffbestände bei diversen nichtenergetischen Anwendungen wie etwa Infrastruktur, Wohnstätten und Waren gefunden, welche sich über kurz- bis langlebige Konsum- und Kapitalgüter verteilen.

Mit dem Ziel, sich hin zu kohlenstoffarmen Volkswirtschaften zu bewegen, wurden in jüngster Zeit einige Strategien zur Verminderung von Ressourcenknappheit und Kohlenstoffemissionen skizziert. Die Strategie der Kreislaufwirtschaft, genauer gesagt der Materialzirkularität (circularity of materials) in AMS in Verbindung mit soziotechnischen und Umweltkontexten, können kritische Probleme wie Klimawandel oder natürliche Ressourcenknappheit in Angriff nehmen. Ein starkes Interesse für das Bewerten und Verstehen von AMS und die notwendige Evaluierung ihrer Zirkularität wird besonders relevant werden. Basierend auf der Methode der Stoffstromanalyse (Material Flow Analysis, MFA) wurde ein wirtschaftsübergreifendes dynamisches Bestands- und Flussmodell (Economy-wide dynamic stock-flow model, EW-SFM) erarbeitet, um die Entwicklung der deutschen Kohlenstoff-basierten AMS zwischen 1929 und 2055 zu charakterisieren, zu analysieren und zu bewerten. Eine solche Dynamik erzeugt beträchtliche Mengen an Post-Konsum-Abfällen und erkennt die aktuellen Effekte von Produktion und Konsumierung auf die Umwelt an. Als eine der am meisten entwickelten, exportorientierten und aufschwingenden Volkswirtschaften der Welt eignet sich dieses Land in exzellenter Weise als Fallstudie für die Untersuchung und Erforschung der Kohlenstoff-basierten AMS-Dynamik.

Die Papier-, Holz- und Plastikindustrie wurden mit der Hilfe von historischen und Szenario-basierten Daten bis 2055 modelliert. Aus einer Service-orientierten Sichtweise und Analyse wurden Informationen über den Bedarf von Rohmaterial, Stoffdynamiken, Post-Konsum-Abfallmengen und -zusammensetzung sowie Kohlenstoff-bezogene Emissionen für CBM-Güter entnommen. Es wurde herausgefunden, dass Holz, das vornehmlich im Bausektor zu finden ist, das wichtigste CBM in der deutschen Anthroposphäre ist (73,7%). Bis 2055 ist eine Reduktion von 13% zu erwarten, welcher durch den sehr wahrscheinlichen Schrumpf der Bevölkerung bedingt ist und Nebenwirkungen auf die eng mit dem Bausektor verbundene Möbel- und Holzwerkstoffindustrie haben wird. Folglich verschiebt sich die Holznutzung in Richtung Energie und deckt hierbei 56% des inländischen Bedarfs. Die Papierindustrie ist anfällig für Veränderungen in den Kommunikationsdiensten, weshalb sie ca. 50% ihres gegenwärtigen Marktanteils verlieren wird. Nichtsdestotrotz werden die neuen Entwicklungen der Anwendungsmöglichkeiten bis 2055 eine konstante inländische Nachfrage von beinahe 20 Mio.t pro Jahr aufrechterhalten. In der Plastikindustrie werden größere Wachstumspotentiale, generiert durch ausländische Absatzmärkte und neuartige Entwicklungen in den Polymermatrizen, die Nachfrage in den nächsten 40 Jahren fast verdoppeln. Dienstleistungen wie zum Beispiel Verpackung und Kommunikation weisen eine schnelle Wachstumsdynamik in der Binnennachfrage auf. Das Modell hat auch gezeigt, dass (1) der Pro-Kopf-Inlandsverbrauch, (2) das Nutzungsverhalten und (3) die Recyclingraten einen signifikanten Einfluss auf die Entwicklung und Dynamik von AMS haben. Konsumgüter haben eine große Auswirkung auf die AMS-Dynamik, ebenso wie die Nutzlebensdauer auf die Bestandsdynamik.

Die Resultate der SRM-Potentiale, welche auf begründeten Annahmen über die Abfallwirtschaft zur Erreichung von Zirkularität basieren, gaben einen Umfang von Papierabfällen in der Post-Konsumphase von 48,2% an, gefolgt von Holzabfällen (Energieholz ausgeschlossen) mit 31,6% und Plastikabfällen mit 19,9%. Da Papierrecycling ein Reifestadium erreicht hat, was zu einer Stagnierung in SRM-Mengen und einer Verminderung von Abfallströmen führte, gewinnen nun der Einsatz und die Ratensteigerung von Holz- und Kunststoffrecycling an Relevanz. Eine potentielle Reduzierung von Gesamtrohstoffe (total raw materials, TRM) zwischen 9% und 25% für Plastik- und Holz-basierte Produkte wurde entdeckt, inclusive Verbesserungen in der Wiederverwertung und das Recycling. Ein Fokus auf die Steigerung des recycelten Anteils von Kunststoffabfällen zur Reduzierung von Kohlenstoffemissionen und Rohstoffbedarfen wurde evaluiert. Schließlich könnten Kohlenstoff-bezogene Emissionen bis 2037 einen Wert von 100 Mt CO2-Äq übersteigen, mit geringeren Anteilen aus Deponieemissionen.

Die Analyse der Dynamik und des Verhaltens von AMS halfen dabei, die Grenzen der Zirkularität von CBM aus einer SEM Perspektive zu verstehen. Aufbauend auf den Szenario-Ergebnissen wurden vier Zirkularitätsindikatoren (circularity indicators) entwickelt, welche auf SRM, Kohlenstoffbestände, Abfällen in der Post-Konsumphase und Kohlenstoff-bezogenen Emissionen basieren. Positive Effekte von Recycling und Wiederverwendung wurden deutlich nachgewiesen. Eine Verringerung von Kohlenstoff-bezogenen Emissionen auf das gegenwärtige Niveau bis 2055 ist möglich, wenn Recycling und Strukturen umweltfreundlichen Konsumverhaltens richtig kombiniert werden.

Schlussendlich, nach einem Prozess der Verifizierung, Validierung und Kalibrierung mit historischen und berechneten Daten, bewies sich das Modell als ein adäquates Instrument für die Evaluation und Dynamik von gesamtwirtschaftlichen AMS, wo die Schätzungsunsicherheiten – ein grundsätzliches Thema in zukünftigen Systemevaluierungen –, benötigt Transparenz bei der Ergebniskommunikation zur Gesellschaft und für eine solide Grundlage zur Gestaltung von Umweltpolitik. Diese Untersuchung hob die Signifikanz und die Relevanz von Kohlenstoff in AMS hervor, um Wissen für die Bewältigung von Kohlenstoffausstößen und die Verminderung des Drucks auf Rohstoffe bereitzustellen und um den Wandel hin zu nachhaltigen kohlenstoffarmen Gesellschaften voranzutreiben.

## Summary

The anthroposphere is the system created by human beings where flows and stocks are deliberately induced through economic, social, biological and cultural activities to outline complex socioeconomic needs, relationships and structures. These activities maintain energy and non-energy (or material) dynamic processes under a socioeconomic metabolism (SEM) perspective. Notwithstanding, environmental pressures are present from demands of resources and raw materials, as these are getting scarcer, as well as from waste management processes. In this sense, anthropogenic material systems (AMS) have become a fundamental object of study as a mean to understand and reduce the impact of material flows and stocks within the economies in the transition from a traditional biogenic resource-based flow-dependent operating capacity to a strong anthropogenic resource-based stock-dependent necessity.

An essential component for the current global *status quo* in energy and material activities at both biogenic and anthropogenic levels is carbon (C). The use of carbon in anthropogenic energy-related activities like transport, electricity generation, and heating, among others, implies carbon emissions promoting human-induced climate change. Nevertheless, carbon emissions can also be potentially released from bounded carbon-based materials (CBM) such as wood, paper and plastics with additional effects in global ecosystems. In this sense, anthropogenic carbon stocks building from consumer and capital goods helps to cope with further carbon emissions illustrating their importance as key pillars in SEM in the development of sustainable resource and carbon management systems. In other words, anthropogenic carbon stocks can become secondary raw materials (SRM) reducing pressures over primary resources, post-consumer waste volumes and carbon-related emissions.

The staggering global production, consumption and trade of carbon-based resources like biomass and crude oil is increasing dramatically the carbon material throughput in the anthroposphere. In Germany, for instance, growing per capita consumption and production rates in services like packaging, transport, communication, construction, among others, have been observed since 1950. Currently, over 90 million tons per year (Mt/y) of carbon-based raw materials are demanded, as novel products and applications are permanently introduced in the markets. The German per capita consumption of CBM is among the highest in the world with expected annual average increases of 1.3% until 2030. Germany has the fourth largest world paper market and the largest European paper, timber and plastic consumption rates. The paper industry has continuously and rapidly grown (around 1.8% annually since 1985) reaching a production of 23 Mt in 2014. The wood industry has increased almost three-fold since 1950 reaching consumption levels of 72.5 million $m^3$ by 2013, with 65% for material use. The plastic industry produced nearly 19.8 Mt of resins for standard and engineered polymers production, growing three times faster than the paper industry. As an effect, large volumes of in-use anthropogenic carbon stocks are found with diverse non-energy applications like infrastructures, dwellings or commodities among others, distributed among short- to long-lived consumer and capital goods.

With the aim of moving towards low-carbon economies, several strategies for abating resource scarcity and carbon emissions have been recently outlined. The circular economy strategy and more in detail the circularity of materials in AMS in combination with sociotechnical and environmental contexts can tackle critical problems as climate change or scarcity of natural resources. A strong interest for evaluating and comprehending AMS and the necessary evaluation of its circularity becomes substantially relevant. Based on the Material Flow Analysis (MFA) methodology, an economy-wide dynamic stock-flow model

(EW-SFM) was developed to characterize, analyze and evaluate the development of the German carbon-based AMS between 1929 and 2055. Such dynamics creates a considerable volume of post-consumer wastes and acknowledges the current effects of production and consumption in the environment. As one of the most developed export-oriented and vibrant economies worldwide, this country becomes an excellent case-study to examine and study the carbon-based AMS dynamics.

The paper, wood and plastic industry were modeled using historical and scenario-based data through 2055. From a service-oriented perspective and analysis, information about raw material requirements, stock dynamics, post-consumer waste volumes and composition, as well as carbon-related emissions for CBM goods were withdrawn. It was found that wood is the largest CBM used in the German anthroposphere (73.7%) concentrated mostly in built environments. A reduction of 13% is expected by 2055 due to the very likely German population shrinkage, with collateral effects in the furniture and panel industry, closely related with the construction sector. Therefore, wood for energy purposes shows a shift reaching 56% of the total domestic demand. The paper industry, susceptible to changes in the communications service, will lose almost 50% of its current market share. Nevertheless, the new developments in paper applications will maintain a constant domestic demand of nearly 20 Mt per year through 2055. In the plastic industry, stronger growth potentials driven by foreign markets in addition to novel polymer matrices developments, will nearly duplicate the demand in the next 40 years. Services like packaging and communication present rapid growth dynamics in the domestic demand. The model also showed that (1) the domestic per capita consumption, (2) the in-use behavior, and (3) recycling rates have significant influence in the AMS development and dynamics. Consumer goods have a large impact in the AMS dynamic, and the in-use lifetime in the stock dynamics.

Findings in SRM potentials, based on reasonable waste management assumptions to achieve circularity, showed post-consumer paper wastes volumes of 48.2%, followed by wood wastes (excluding energy wood) with 31.6% and closing with plastics wastes (19.9%). Since paper recycling reached a mature stage, leading to stagnation in SRM volumes and reduction in waste outflows, the deployment and increased rates for wood and plastics recycling become relevant. A potential reduction of total raw materials (TRM) between 9% and 25% for plastic and wood-based products with recovery and recycling improvements was detected. A focus in increasing the recycled share of plastics wastes to reduce carbon-emissions and raw material requirements was evaluated. Finally, carbon-related emissions may exceed 100 Mt $CO_2$-eq by 2037, with lower shares from landfill emissions.

The analysis of the AMS dynamics and behavior helped to comprehend the limits of circularity of CBM under a SEM perspective. Based on the scenario results four circularity indicators were developed based on SRM, carbon stocks, post-consumer wastes and carbon-related emissions. Positive effects of recycling and reuse were clearly proven. A cutback of carbon-related emissions to current levels by 2055 is possible, if recycling and environmental-friendly consumption behavior patterns are properly combined.

Finally, following verification, validation and calibration processes with historical and estimated data the model showed to be an adequate tool for the evaluation and dynamics of economy-wide AMS, where defining uncertainties are a fundamental topic for future systems evaluations, transparency in results communication to the society and solid foundation for environmental policy making. This research highlighted the significance and relevance of carbon in AMS to provide knowledge for coping with carbon emissions and pressure reductions in raw materials to shift towards sustainable low-carbon societies.

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## List of acronyms

| | |
|---|---|
| ABS | Acrylonitrile Butadiene Styrene |
| AMS | Anthropogenic material system |
| BtL | Biomass-to-Liquid |
| BMUB | German Ministry for the Environment, Nature Conservation, Building and Nuclear Safety |
| CBA | Cost-Benefit Analysis |
| CBM | Carbon-based materials |
| CE | Circular economy |
| CEPI | Confederation of European Paper Industries |
| $CH_4$ | Methane (gas) |
| $CO_2$ | Carbon dioxide (gas) |
| $CO_2$-eq | Carbon dioxide equivalent |
| COP | Conference of Parties |
| DESTATIS | German Statistical Office |
| DSFM | Dynamic stock-flow model |
| EFA | Ecological Footprint Analysis |
| EF | Ecological Footprint |
| EIO | Environmental Input-Output Analysis |
| EN | European Norm |
| EPS | Expanded Polystyrene |
| EU27 | European Union (27 member states) |
| EUROSTAT | Statistical office of the European Union |
| EW-MFA | Economy-wide Material Flow Analysis |
| EW-SFM | Economy-wide stock-flow model |
| FAO | Food and Agriculture Organization |
| GDP | Gross Domestic Product |
| GHG | Greenhouse Gases |
| HDPE | High Density Polyethylene |
| IE | Industrial Ecology |
| ILG | In-use lifetime groups |
| IO | Input-Output Analysis |
| IOT | Input-Output Tables |
| IPCC | Intergovernmental Panel on Climate Change |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCC | Life Cycle Costing |
| LDPE | Low Density Polyethylene |
| MCS | Monte Carlo Simulation |
| MFA | Material Flow Analysis |
| MIPS | Material Input per Unit of Service |
| MRIO | Multiregional Input-Output Analysis |
| Mt | Million tons |
| $N_2O$ | Nitrous oxide (gas) |
| OECD | Organization for Economic Co-operation and Development |
| OP | Other Polymers |
| OT | Other Thermoplastics |
| PA | Polyamide |
| PET | Polyethylene-terepfhthalat |

| | |
|---|---|
| PIK | Potsdam Institute for Climate Impact Research |
| PIOT | Physical Input-Output Tables |
| PMMA | Poly(methyl-methacrylate) |
| PP | Polypropylene |
| PRM | Primary raw materials |
| PS | Polystyrene |
| PU | Polyurethane |
| PVC | Polyvinyl-chloride |
| QSA | Quantitative Sensitivity Analysis |
| REACH | Registration, Evaluation and Authorization of Chemicals (ER1907/2006) |
| SFA | Substance Flow Analysis |
| SLCA | Social Life Cycle Assessment |
| SRC | Standardized Regression Coefficients |
| SRM | Secondary raw materials |
| SEM | Socioeconomic metabolism |
| TRM | Total raw materials |
| UNECE | United Nations Economic Commission for Europe |
| UNFCCC | United Nations Framework Convention on Climate Change |
| WEEE | Waste Electrical and Electronic Equipment |
| WIO | Waste Input-Output Analysis |
| WTO | World Trade Organization |

## List of symbols

| | |
|---|---|
| $a_j$ | Product weighting fraction within market share (%) |
| $A_{i,t}^{\omega}$ | Allocation factor in waste treatment process |
| $(A/B)_t$ | Circularity indicator |
| $C_{i,t}$ | Carbon content in raw materials for combustion processes (kt/a) |
| $C_{j,t}$ | Carbon content in material groups for combustion processes (kt/a) |
| $C_t$ | Total carbon content in materials for combustion processes (kt C/a) |
| $\dot{C}_t$ | Carbon-related emissions from combustion processes in $CO_2$-eq (kt/a) |
| $c_{i,t}$ | Elementary carbon concentration in raw materials (%) |
| $c_{j,t}$ | Elementary carbon concentration in material groups (%) |
| $CpC_t^{mg,ser}$ | Per capita consumption per service and material at period *t* (kg/cap) |
| $CpC_{t0}^{mg,ser}$ | Per capita consumption per service and material at initial period (kg/cap) |
| $CpC_{tf}^{mg,ser}$ | Per capita consumption per service and material at final period (kg/cap) |
| $CpCW_t^{mg}$ | Average foreign per capita consumption per material group (kg/cap) |
| $d$ | Minimum, maximum or expected discard time of product *j* (a) |
| $D_t$ | Domestic demand (t/yr) |
| $D_{j,t-y}$ | Domestic consumption of product group *j* at period $t - y$ (kt/a) |
| $D_{j,t}^{C}$ | Domestic demand per product group estimated with per capita consumption (kt/a) |
| $D_{j,t}^{H}$ | Domestic demand per product group estimated with production coefficients (kt/a) |
| $D_t^{ig}$ | Domestic demand of each in-use lifetime group (kt/a) |
| $D_t^{mg}$ | Domestic demand of each material group (kt/a) |
| $D_t^{mg,ig}$ | Domestic demand per material and in-use lifetime group (kt/a) |
| $f(t, t_0, \alpha_t, \beta_t)$ | Probabilistic value of rate of discard per period and in-use lifetime group |
| $F_t$ | Domestic energy goods (kt/a) |
| $GWP_t$ | Global warming potential value |
| $h_{i,j}$ | Production function coefficient |
| $IP_t^{mg}$ | Material group import propensity factor (%) |
| $k$ | Methane generation rate (1/a) |
| $L_t^{CH4}$ | Methane emissions from landfill activities (kt/a) |
| $L_t^{CO2}$ | Carbon emissions from landfill activities (kt/a) |
| $m$ | Number of products groups |
| $mg$ | Subindex for material group |
| $MS_{j,t}^{mg}$ | Market share per material and product group (%) |
| $n$ | Number of processed raw materials |
| $pg$ | Subindex for product group |
| $PopW_t$ | Trading capable population (million) |
| $R_{i,t}$ | Required processed raw material *i* for period *t* (kt/a) |
| $\dot{R}_{i,t}$ | Residual required processed raw material *i* for period *t* (kt/a) |
| $\bar{R}_{i,t}$ | Adjusted required processed raw material *i* for period *t* (kt/a) |
| $R_{i,j,t}$ | Required processed raw materials for product group *j* (kt/a) |
| $R_t^{dom}$ | Domestic processed primary raw materials (kt/a) |
| $R_t^{imp}$ | Imported processed primary raw materials (kt/a) |
| $R_t^{exp}$ | Exported processed primary raw materials (kt/a) |

| | |
|---|---|
| $R_{i,t}^{dom}$ | Domestic processed raw material *i* for period *t* (kt/a) |
| $R_{i,t}^{imp}$ | Imported processed raw material *i* for period *t* (kt/a) |
| $R_{i,t}^{*}$ | Primary required processed raw materials *i* for period *t* (kt/a) |
| $R_t^{\prime exp}$ | Exported secondary raw materials (kt/a) |
| $R_t^{\prime re}$ | Potential recycled raw materials (kt/a) |
| $R_t^{\prime man}$ | Recycled raw materials to manufacturing sector (kt/a) |
| $R_t^{\prime inc}$ | Non-suitable recycled raw materials to incineration (kt/a) |
| $S_t^{ig}$ | Stocks in period *t* per in-use lifetime group (kt) |
| $S_0$ | Initial stocks value in period $t_o$ (kt) |
| $S_t$ | Total stocks value in period $t_o$ (kt) |
| $ser$ | Subindex for service |
| $t$ | time or period *t* |
| $t_\Delta$ | Inflexion period (a) |
| $t^{ig,d}$ | Discard time per in-use lifetime group (a) |
| $t_{j,d}^{ig}$ | Discard time of product *j* per in-use lifetime group *ig* (a) |
| $V^g$ | Combustion gas composition (%) |
| $W_t$ | Post-consumer waste (kt/a) |
| $W_t^{ig}$ | Post-consumer waste per in-use lifetime group (kt/a) |
| $W_{j,t}^{ig}$ | Post-consumer waste per in-use lifetime group and product group (kt/a) |
| $W_t^{ig,\omega}$ | Post-consumer waste for waste treatment per in-use lifetime and material group (kt/a) |
| $W_t^{mg,ig}$ | Post-consumer waste per material and in-use lifetime group (kt/a) |
| $W_{t'}^{ig}$ | Post-consumer waste from a specific period for waste treatment (kt/a) |
| $W_t^{imp}$ | Imported post-consumer waste for waste treatment processes (kt/a) |
| $W_t^{man}$ | Post-industrial waste (kt/a) |
| $W_{i,t}^{man,\omega}$ | Post-industrial raw material waste to waste treatment processes (kt/a) |
| $W_t^{imp}$ | Imported post-consumer waste for waste treatment processes (kt/a) |
| $W_t^{ldf}$ | Post-consumer waste for landfills (kt/a) |
| $W_{j,t}^{\omega}$ | Post-consumer waste per product group to waste treatment process (kt/a) |
| $W_{j,t}^{re}$ | Post-consumer waste for recycling per product group (kt/a) |
| $WD_t^{ig}$ | Probabilistic change in expected discard in post-consumer waste volumes (t) |
| $X_{j,t}$ | Domestic manufactured goods for product group *j* (kt/a) |
| $X_{j,t}^{M}$ | Domestic production for product group *j* estimated with flows (kt/a) |
| $X_{j,t}^{H}$ | Domestic production for product group *j* estimated with production coefficients (kt/a) |
| $X_t^{dom}$ | Domestic manufactured goods (kt/a) |
| $X_t^{exp}$ | Exported goods (kt/a) |
| $X_t^{exp,mg}$ | Exported goods from each material group (kt/a) |
| $X_{j,t}^{exp}$ | Exported goods per product group (kt/a) |
| $X_t^{imp}$ | Imported goods (kt/a) |
| $X_{j,t}^{imp}$ | Imported goods per product group (kt/a) |
| $X_t^{imp,mg}$ | Imported goods of each material group (kt/a) |
| $X_t^{ru}$ | Reused or refused goods (kt/a) |

| | |
|---|---|
| $X_{j,t}^{ru}$ | Reused or refused goods of product group j (kt/a) |
| $y$ | Year of discard (yr) |
| | |
| $\alpha_t^{ig}$ | Scale parameter in probability function |
| $\beta_t^{ig}$ | Shape parameter in probability function |
| $\Delta S_t$ | Stock change in the anthroposphere (kt/a) |
| $\epsilon_t^{mg}$ | Material group export propensity factor (%) |
| $\eta_{mg}^{man}$ | Manufacturing efficiency per material group (%) |
| $\eta_{mg}^{re}$ | Recycling depollution factor per material group (%) |
| $\Phi_y^{ig}$ | Probability density function of the in-use lifetime groups at discard period |
| $\phi_t^{ig}$ | Probabilistic discard value from probability density function $\Phi(ig,y)$ |
| $\gamma_x$ | Linear regression coefficient |
| $\Gamma_x$ | Standardized linear regression coefficients |
| $\kappa_t$ | Country's world export share (%) |
| $\mu_{i,j}$ | Iteration value (kt/a) |
| $\nu^{mg}$ | Methane generation potential per material group ($tCH_4$/tWaste) |
| $\rho_t^{ig,\omega}$ | Distribution factor for waste treatment $\omega$ (%) |
| $\sigma_x$ | Standard deviation of input factor $x$ |
| $\sigma_y$ | Standard deviation of output factor $y$ |
| $\tau$ | Transition period coefficient (a) |
| $\omega$ | Waste treatment process (recycling, incineration, landfill) |
| $\xi$ | Stoichiometric combustion ratio |

# 1. Anthropogenic flows and stocks in material systems

> „Die Spirale liegt genau dort, wo die leblose Materie sich in Leben umwandelt. Ich bin davon überzeugt, daß der Schöpfungsakt sich in Spiralform vollzogen hat. Unsere Erde beschreibt den Lauf der Spirale. Wir gehen im Kreis, aber wir kommen nie wieder an den Punkt zurück, der Kreis schließt sich nicht, wir kommen nur in die Nähe des Punktes, wo wir gewesen sind.“
>
> **Friedensreich Hundertwasser, Austrian artist (1928 – 2000)**

The pre-Socratic Greek philosopher Heraclitus of Ephesus recognized one fundamental fact about the physical world. He acclaimed more than 2,400 years ago, as affirmed in Plato's Cratylus and taking as analogy the moving waters of a river, "all things move and nothing remains still" (Fowler, 1921). Later coined as *panta rhei*, everything flows; it describes states of dynamic balance, like a moving stream of a river at constant level. Such patterns can be scaled up at all stages from the subatomic to macroscopic domains. At the latter, material and energy flows create permanently, based on relationships of inflows, outflows, stocks, feedback loops and driving forces, substances and matter to develop inorganic and organic chemical compounds allowing, for instance, the appearance of life and humankind. Dynamic material and energy flows are proper characteristics of complex systems. For example, in living organisms these are required to satisfy immediate needs, metabolic purposes and to maintain its vital functionality. The extension from living organisms to the societal domains is not straightforward (Capra and Luisi, 2014), but it provides a blueprint for understanding these types of systems. Under this perspective, the active complexity of society's networks also emulate the autopoietic characteristics of organization and self-maintenance (Capra, 2002) and encloses, as coined by Fischer-Kowalski and colleagues (1998), a set of processes that describe a societal metabolism or, as known nowadays, a socioeconomic metabolism or SEM (Krausmann et al., 2008; Schandl et al., 2015; Pauliuk et al., 2015a). SEM points out the material, substance and energy throughput of socioeconomic systems, which means all the biogeophysical resources required for production, consumption, trade and transportation within a society (Haberl et al., 2013). Further, it defines the structure and properties of functional self-maintained anthropogenic processes compromising all activities and goods humans needs in the anthroposphere (Isenmann, 2003), understood as a system created by humans where flows and stocks[1] deliberately induced through economic, social, biological and cultural activities takes place for the satisfaction of human needs (Brunner and Rechberger, 2004; Baccini and Brunner, 2012).

As a result of these permanent dynamic and circular patterns of causality, diverse activities within the societal metabolism are creating tensions and pressures in several coexisting anthropogenic natural systems. At the environmental level, the rates of depletion and overuse of water, land, biomass and many other natural resources (flows) show strong signs of stress and deterioration in ecosystems, higher risks and threats in populations and wildlife, scarcity of available natural resources, among others (Worldwatch Institute, 2015). Even more, recent studies show that mankind has already crossed four of nine environmental equilibrium states or planetary boundaries[2], deteriorating human well-being, increasing poverty and reducing

[1] Aside from material and energy flows and stocks, additional flows and stocks of knowledge, information and money have also appeared at an anthropogenic level, complementing the complex network of society. The latter three, however, lie outside the scope of this work.

[2] The four affected planetary boundaries are: climate change, loss of biosphere integrity, land-system change, altered biogeochemical cycles, not to mention that in some regions more boundaries have been already crossed.

resilience of the entire planet (Rockström et al., 2009; Steffen et al., 2015). There is no single final solution for these concerns. Notwithstanding, a rising need in understanding the structure and functioning of anthropogenic systems, like the throughput analysis of material value chains including extraction, processing, manufacturing, consumption and specially waste management provides a strong framework and tool for tackling these challenges. Furthermore, the increased pressures on biogenic natural resources, to satisfy the growing consumption rates of society, have raised the interest in circular strategies in the materials system to reduce the impact in the environment caused by extraction, use and carbon emissions to the atmosphere from materials and energy use. In this sense, anthropogenic flows and stocks are increasingly gaining importance not only at the political and economic level (Daxbeck et al., 2009; Schmidt, 2010; Schmidt et al., 2010), but also as they have proved to affect the Earth's ecological equilibrium seen in climate change, acidification of oceans, reduction of biodiversity, depletion of ecosystems, among others (Steffen et al., 2015). In other words, the study of anthropogenic flows and stocks provides an insight for the preservation and conservation of the environment, wildlife and human beings. Further, human-based systems should be described, assessed and evaluated under material stock-flow systems for environmental assessments and management of activities and processes occurring in the lithosphere, the biosphere, the atmosphere, and, most important, in the anthroposphere.

Parallel to the growing scarcity of natural resources, the changing climate conditions of the biosphere are increasingly noticeable (IPCC, 2014). Since the late 19th century, the staggering volumes of carbon emission have provoked what some call the human-induced climate change. Carbon emissions are mainly associated with energy use, where carbon dioxide ($CO_2$) is the main process waste that contributes to the atmospheric greenhouse effect. The principal sources of $CO_2$ are the combustion of fossil fuels and biomass energy carries for anthropogenic activities such as transport, electricity generation, household and industry heating, among others. Nevertheless, carbon emissions must also be associated with the development of infrastructure or built environment stocks (Müller et al., 2013) and moreover with the stocks of carbon-based materials (CBM) like wood, paper or plastics that store or binds temporarily carbon (Gielen, 1997). Studies of carbon stocks have been focused in natural (biogenic) cycles; however, the impact of anthropogenic carbon stocks cannot be underestimated (Kohlmaier et al., 2007; Rüter, 2008; Köhl et al., 2009; OECD, 2010a). Carbon stocks in the anthroposphere can potentially release significant amounts of carbon-related emissions to the atmosphere with effects in global ecosystems (Pingoud et al., 2003; Patel et al., 2005). Although there is a lack of a consistent and systematic definition of "carbon accounting" (Stechemesser and Guenther, 2012), the measuring of the release of carbon emissions is one of the most important environmental challenges and problems humanity is currently facing with political implications (Daxbeck et al., 2009; IPCC, 2014), as carbon emissions should be stabilized in the coming decades to maintain the global temperature rise under two degrees Celsius. Because of its imminent effects, this target, now a universal agreement after the UNFCCC COP 21 in Paris, appeals efforts in limiting the temperature increase even below 1.5 degrees above pre-industrial levels (UNFCCC, 2015). Nonetheless, carbon stocks are potential sinks that avoid additional emissions to the atmosphere. Under an accurate use and waste management, a delay or cut in the carbon emissions from such carbon stocks could be achieved. For an accurate understanding of the dynamics of carbon stocks and flows, anthropogenic sources must be considered, and the interest in a rigorous carbon accounting has increased within the scientific community (Shirley et al., 2011).

Because of the current techno-economic development pace of societies and its soaring volume use of materials and energy in economy-wide activities, transitions and shifts from natural environments resource extraction to anthropogenic ones will likely take place (Krausmann et al., 2008; Chen and Graedel, 2015). The practice and research in urban mining (Schiller et al., 2015), metal stocks being one example (Kapur and Graedel, 2006; Glöser et al., 2013), indicates a transition from the traditional flow-dependent operating capacity of the economies supported by natural resources, to a strong stock-dependent necessity within anthropogenic material systems (AMS). To achieve such intention, the knowledge of future material stocks, and composition, volumes, and type of post-consumer waste is necessary. Thus, the study of anthropogenic flows and stocks helps to evaluate current and future situations of (1) primary and secondary raw materials demand, (2) material cycles in ever broadening product consuming societies, (3) waste generation and treatment, (4) accumulation of material with hazardous and non-hazardous effects and (5) estimation and reduction of carbon emissions. As a consequence of the above mentioned circumstances, an assessment of carbon-based material cycles within anthropogenic systems, especially in material flows and stocks with large environmental potential effects in global-scale challenges like climate change, becomes essential.

This work intends to add a significant contribution to the studies of anthropogenic flows and stocks in material systems, specifically in future carbon flows and stocks as a further step in the development of sustainable carbon management systems. Based on the analysis of selected carbon-intensive material industries and its respective CBM, possible developments under the perspective of SEM are studied to elucidate paths into low-carbon circular economies. As mentioned above, CBM are paper, wood, plastic and rubber, and indicate materials with significant carbon content in its elementary composition. Having this context in mind, this work will focus on the following research questions: (1) what is the expected development and dynamic of an economy-wide carbon-based material system under a socioeconomic metabolism perspective in Germany?, (2) what potential opportunities are foreseeable in the coming decades for efficient management of carbon-related resources, post-consumer wastes and related emissions?, and (3) to what extent can circularity of an anthropogenic carbon-based material system be achieved to create carbon sinks and tackle current environmental burdens? The first question explores quantitatively the amounts of required resources, consumed goods, built stocks and generated post-consumer waste for the near future of selected carbon-based materials, that is paper, wood, plastics and rubber, in the anthroposphere considering current and plausible socio-technical and environmental-related factors. The second question investigates possibilities under a scenario approach of finding systemic relationships between the carbon-based material system variables and activities like material substitution, reuse, recycling, downcycling, cascade use or changes in consumption patterns among others, for a more efficient environmental management. The third question opens the discussion on advantages and disadvantages in achieving material circularity and elucidates possible strategies for a more sustainable dynamic balance in the carbon-based AMS in Germany, based on proposed circularity indicators.

To obtain consistent and concrete answers to the research questions, a dynamic stock-flow model suitable to describe, evaluate and estimate the behavior of material systems at an anthropogenic level for CBM, is developed. This will help to understand the behavior of AMS and evaluate environmental problems and challenges under a societal metabolism perspective. A main pillar for the parallel economy growth and protection of the environment begins by studying the role of stocks and flows of material systems in the anthroposphere. The protection of finite and renewable resources, the rational management of post-industrial and post-consumer waste discarded in the environment and the development of strategies to cope with carbon emissions at technical and societal level are forthcoming variables that should be studied and addressed. Thus, a detailed study and analysis under a scenario approach of economy-wide flows and stocks from carbon-based final goods is performed, within an environmental and socio-technical context considering resource and waste management perspectives. The appropriate understanding of carbon flows and stocks behavior and dynamics within AMS should clarify the relationships between carbon resources, consumption behavior, stock building, waste generation and carbon emissions, and become a complementary tool for future assessments in the carbon management context. The model and study of AMS will focus on Germany as case study, as the consumption of CBM has increased in the last decades in Germany (Consultic, 2013; Weimar, 2013; VDP, 2013a). Also, taking into account its historic development of sustainable policies and actions, in addition to its economic and technological strength, the country becomes an excellent case-study to examine a material system from an anthropogenic perspective. Under an economy-wide perspective the present and future German material system for paper, wood, plastic and rubber, as carbon-based materials, will be estimated.

The work is constructed over a strong theoretical framework discussed in chapter 2, followed by a thorough presentation and description of the developed economy-wide stock-flow model in chapter 3. The application of the model to evaluate carbon flows and stocks using three important carbon-based industries is presented in chapter 4, after discussing the state of the art of these industries. The presentation of results is given in chapter 5. The analysis and discussion of results are found in chapter 6. The conclusions of the work are given in chapter 7. Additional and complementary information used for modeling, including the mathematical equations, sensitivity and uncertainty analysis and supplementary data are presented in the annexes.

## 2. Systemic understanding of socioeconomic metabolism

### 2.1. A scope of socioeconomic metabolism

The biological concept of metabolism mentioned in chapter 1 describes the regulating process of living organisms to attain dynamic balances from material and energy requirements. This homeostatic characteristic of self-maintained systems keeps equilibrium despite the fact that these are open-systems. In other words, they depend on a constant inflow and outflow of material to maintain functionality. The AMS is an open-system as it requires a permanent inflow of material and energy, and on the other side, it has outflows that conserve the dynamic balance of the whole system. This concept, however, reflects a "take, use and discard" process, which can be seen as a linear process. Systems with these characteristics may have, first, very low resilience as they depend on external factors, and second, a high material and energy turnover, leading to a permanent pressure for accessing resources and generating high volumes of wastes. At the anthropogenic level, such systems are unsustainable and prone to collapse by lack of resources or by degradation and pollution of the surrounding environment. As a consequence of the rising demands of materials in the last decades used for industrial and economic activities in a race to achieve welfare within societies, both renewable and non-renewable resources are showing signs of overuse or scarcity (Rockström et al., 2009; Steffen et al., 2015), while pollution of urban and non-urban soil, water and air systems and associated socioeconomic problems are still present and increasing. Under this perspective, as mentioned in chapter 1, Fischer-Kowalski and Hüttler (1998) introduced the term "societal metabolism" at the beginning of the last decade to draw the attention in the description and evaluation of material systems as a tool for coping environmental concerns. Also known as "socioeconomic metabolism" or SEM (Krausmann et al., 2008; Schandl et al., 2015; Pauliuk and Hertwich, 2015; Pauliuk et al., 2015a), "metabolism of the anthrosposphere" (Baccini and Brunner, 2012) or "anthropogenic metabolism" (Brunner and Rechberger, 2002), it refers to the material, substance or energy throughput of socioeconomic systems, meaning all the natural and anthropogenic resources required for manufacturing, consumption, trade, transportation and post-consumer activities (Haberl et al., 2013) to satisfy human requirements and purposes. In this work the term socioeconomic metabolism (SEM) will be preferred.

The SEM concept has aligned economic, social and environmental aspects about the use of natural and anthropogenic resources at material and energy levels comprising extraction, transformation, distribution processes based on flows and stocks relationships (Brunner and Rechberger, 2004; Baccini and Brunner, 2012; Pauliuk and Hertwich, 2015; Schandl et al., 2015). Therefore, it can also measure large-sized anthropogenic systems such as regions, countries or the whole world in a systematic way and comprises the identification and quantification of material flows and stocks. For some authors, the ultimate goal of SEM is to bring the capacity to systematically and adequately interpret environmental data, resources and system dynamics to design successful adaptation and mitigation strategies for the coming environmental challenges (Pauliuk and Hertwich, 2015). The AMS dynamics describe the permanent throughput of flows and stocks within the anthroposphere and reflect the basic nature of SEM (Pauliuk and Müller, 2014).

Far from being a linear-consequential phenomenon, SEM attains a dynamic balance on the basis of a complex network and relationships between the system components (Brunner and Rechberger, 2004). It integrates feedback loops and non-deterministic human patterns at material and energy levels, that have an influence in the autopoietic characteristics of the system (Capra and Luisi, 2014). From this perspective on, the SEM concept goes further than the accounting of material and energy to evaluate specific aspects of the process and networks within the anthroposphere driven by a complex system of factors. Several phenomenological aspects at social, technical, economic, or environmental level, such as resource availability, exploitation and manufacturing technologies for resources and goods, socioeconomic development and consumption patterns, among others, play a significant role for determining the anthropogenic metabolism. Sociotechnical variables include (1) in-use lifetime of goods, (2) process manufacturing efficiencies, (3) material composition and design of finished products, (4) consumer behavior, or (5) consumption and purchasing preferences, among others. For environmental-related variables it is found, (1) type of solid waste treatment processes, (2) eco-efficiency, (3) substitution potentials of materials between renewable and non-renewable sources, or (4) use of secondary raw materials. The study of these variables provides a deep understanding and perspective of the dynamics of stock-flow material systems in the anthroposphere. Thus, the SEM concept is suitable for studying topics such as circularity in economies, stocks dynamics or effects of human consumption patterns to provide substantial knowledge about the structure and behavior of AMS.

### 2.1.1. Circular economy and recycling in AMS

SEM helps to describe the best way the AMS can achieve efficient use of resources (primary and secondary raw materials) along their life cycle, considering consumption, use and waste management dynamics. These resource-efficient strategies are being discussed to promote shifts in economic paradigms. The term "circular economy" appears in the political sphere as a strategy to develop sustainable business models where wastes are used (Tuppen, 2015) and emissions mitigated (Haas et al., 2015). A circular economy can be developed under cascade use of resources and by-products, decoupling of consumption, resources and energy, improvement of waste management processes, among others. At the material systems level actions like product responsibility (ecodesign, recyclability and consumer behavior), optimization of recycling or prevention of illegal exports are being approached. These advances show that decoupling economic growth from pollution and resource efficiency is now recognized by the global policy community (Schandl et al., 2015). At a regional level, the European Commission defined in 2015 a still-in-progress circular economy strategy for a "more competitive resource-efficient economy, addressing a range of economic sectors, including waste" (EC, 2015a; EC, 2015b). Even further, the 2012 German Resource Efficiency Programme (ProgRess) from the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) seek the decoupling of economic growth from resource use, the reduction of environmental impacts of resource use and improve the sustainability and competitiveness of the German industry (BMUB, 2015).

One of the critical flows concerning environmental analysis in an economy-wide perspective, are the post-consumer wastes. Once a product has fulfilled its purpose (provided by a service) the manufactured good is discarded (now post-consumer waste) generating the need of replacement with another one. In linear economies a "cradle-to-grave" process chain takes place and the post-consumer flow ends in sinks (air, land or water). In ideal circular economies the outflow is input of further processes and products and the perspective changes to a "cradle-to-cradle" concept, where the sinks become new sources and their relevance in the AMS is reduced. A key strategic measure for establishing a circular economy in material systems is the appropriate management of wastes, especially through the permanent flow and use of secondary raw materials in the manufacturing of new products from recycled flows. In recent decades a growing interest in the recovery of materials from waste outflows have strengthened waste management policies and promote the deployment of recycling technologies as a strategy for increasing secondary resources and take advantage of the resources found in the technosphere. The interest of using waste as a source for secondary raw materials promotes recycling.

As it was once an important part of the economies during the World War times, modern society draws attention to recycling again in the 1960s and 1970s. Recycling is understood as the means to transform waste materials into usable materials for further manufacturing and process cycles, excluding energy recovery, with the aim of reducing primary raw material consumption, energy use and ameliorate air and water pollution from landfilling and incineration waste management practices (Kozlowski, 2006; Michaud et al., 2010; Martens, 2011a; Fröhling et al., 2013). Normally recycling is taken as a synonym of mechanical recycling where the chemical structure of the material is not significantly changed. However, additional types of recycling like feedstock or chemical recycling and biological recycling are present (Martens, 2011a). With the perceived increase in the world demand of primary resources (Schiller et al., 2015) using secondary raw materials contributes to the protection of natural resources reducing materials and energy pressures and coping other environmental threats such as climate change, water scarcity or desertification, among others (UBA, 2009). A proper waste management should lead, under an appropriate approach, to pressure reduction in demand of new resources and other environmental impacts without compromising the manufacturing demands and satisfaction consumer needs within the anthroposphere. Further, the recycling of waste is an effective mechanism for closing material loops in an economy-wide perspective.

Despite the relatively straightforward process, recycling processes face several challenges. First, additional waste management process are used and available. In fact, the most propagated and historical used waste treatment processes are incineration and landfilling. The former consists of the thermal oxidation of materials with the option of energy recovery (Lahl and Steven, 2009; Richers, 2010). The latter accumulates solid wastes in determined dumping sites to be decomposed mostly by anaerobic processes (Young, 2010). Both mechanisms are cost-efficient but cause the emissions of greenhouse gases (GHG) like carbon dioxide ($CO_2$) or methane ($CH_4$), well known for contributing to global warming. Second, the increasing material complexity of manufactured goods and use of additional synthetic (mostly organic) substances, such as fire retardants in electronic components (Vyzinkarova and Brunner, 2013) or chemical treated woods (Banks, 2001), have given several connotations to the complete recycling process. Third, the constant innovation and introduction of new products brings challenges to the traditional recycling processes (Martens, 2011c; Martens, 2011d). In fact, the European regulation 1907/2006 on Registration, Evaluation and Authorization of Chemicals (REACH), although in principle not intended for waste directly, illustrates the difficulty of assessing hazardous substances used in manufactured products with negative environmental fates within waste treatment process (Bimboes and Braedt, 2008). Because of the material composition and characteristics in the different finished goods, the recycling of products requires specific waste sorting and recovery treatments. Finally, the homogeneity in the quality of secondary raw materials is also a main challenge (Pauliuk et al., 2011) for reaching the goals of a circular economy.

### 2.1.2. Circularity instead of circular economy

Drivers of AMS like population dynamics or human behavior not only have effects in the economy and demand of materials. The circular economy concept should reach other areas of the society. Aspects, like consumer patterns, politics, businesses, among others, influence and complement the material systems technical and material perspective in the anthropogenic system. Thus, the idea of circular economy must transcend the economic level or scope and should seek "to rebuild capital, whether this is financial, manufactured, human, social or natural (...) [to ensure] enhanced flows of goods and services" (Tuppen, 2015). A reason for this is that several current economic systems are based on the fallacious concept of eternal economic growth and many environmental impacts (like externalities) cannot be measure with economic indicators. Within the circular economy paradigm, the term *circularity* should be used, as this goes beyond the economic sphere and maintains the principles and essence of dynamic balances and systemic behavior of a system in the anthroposphere. Circularity is a broad concept that involves a large number of stakeholders and contexts, like economy, society, demographic, technology, politics, energy and material spheres and environment.

From the material perspective circularity is maximized when the open system is closed and the dependence of external inflows and outflows are reduced for keeping the dynamic balance of the material system, parallel to a stable and sufficient dynamic stock in service for the satisfaction of needs. Notwithstanding, the material cycle cannot be fully closed. Circularity is achieved when the demand of primary raw materials and the discarded non-recoverable residues from post-industrial and post-consumer wastes reaches a minimum volume. From a thermodynamic perspective, the second law (law of dissipation) describes a permanent and inevitable loss of non-recoverable materials. Additionally, this law also establishes the limits of a recyclability of materials. Both conditions are completely related with the availability of secondary raw materials.

Further, the consumption of goods today will determine the wastes in the future. Achieving circularity goes beyond the technical sphere. Consumption patterns and social behavior strengthens activities like the reuse of discarded products (Haas et al., 2015) can be also considered as contributing actions to close material loops. Even more, variables at political and environmental spheres complement the description of a general approach for the paradigm of circularity. From a network of networks perspective and under systemic thinking any network is a flexible structure independent of the external conditions (Capra and Luisi, 2014). Thus, every studied AMS (say in developing or developed economies) should share common type of relationships. From the systemic view, circularity is the result of a combination of factors webbed in a network of flows and stocks. In other words, the principles of circularity must follow a universal pattern.

Translating the abstract concept of circularity into the material systems requires the use of methods and models. Thanks to several modeling methods the material demand at industrial, municipal, national and global spheres has been, and is still being, quantified giving support and pertinent information about the states and changes inside the AMS. In a relative new scientific field of research, known as "industrial ecology", several methods for the evaluation of different aspects of the SEM and circularity are found (Bringezu, 2003; Pauliuk and Hertwich, 2015) and are discussed as follows.

## 2.2. The industrial ecology (IE) methods toolset

The rise of environmental challenges and threats have obliged environmental researchers to describe in proper and accurate terms natural and anthropogenic surroundings with the aim of increasing the understanding of material stocks and flows of resources in a system along time (Brunner and Rechberger, 2004; Weisz et al., 2015; Wiedmann et al., 2015). The study of stocks and flows in material systems lies within the SEM concept. Past and present events like exploitation of natural resources, development of built environments, post-consumer waste generation or implementation of urban mining and future circumstances like the depletion of natural resources or recovery of secondary raw materials can be thoroughly modeled and described within the SEM approach. Having in mind the main aspects that describe and characterize AMS, it is necessary to introduce the main methods used in the description and understanding the metabolism of the anthroposphere. The multiple feedbacks and relationships of global environmental processes build-up complex systemic structures of flows and stocks (that is known flows, hidden flows, in-use stocks and hibernating stocks) at the various layers and scales (Bringezu et al., 2003; Fischer-Kowalski et al., 2011). Such networks allow a constant interaction between humans and the environment and are thoroughly described by material and energy flows in natural and industrial systems. Nevertheless, its activities and products create, in some cases, a non-intended burden in the environment, reaching sometimes disruptive limits in ecosystems. These effects can be localized at any point between the supply level from primary and secondary resources, with depletion or destruction of ecosystems and the waste treatment processes, with generation of toxic or hazardous wastes. Thus, the study of these densely interconnected systems in industrial and natural environments have the objective of (1) advancing towards a sustainable economy, (2) understanding flows and stocks behavior under SEM approach and (3) providing groundwork for strategic decisions or policies. This branch of knowledge is known as "industrial ecology" (IE) and represents an interdisciplinary field of study between industrial systems and nature (Isenmann, 2003). In principle, IE focus on creating links between the industry, society and the environment, concerning mostly environmental impacts of anthropogenic activities at local, regional and global level under a circularity perspective.

Over the last century a large multidisciplinary number of methods and approaches were developed in an effort to model industrial and manufacturing processes. Notwithstanding, in the last three decades, the application of these methods has focused strongly at an environmental level. Starting from the works of Graedel and Allenby (2003) or Ayres and Ayres (2002) among other "founding fathers" of industrial ecology, a deeper comprehension of flows and stocks in material systems has been achieved. More recently, the study and understanding of the dynamics of stocks (van der Voet et al., 2002; Müller, 2006) focusing on sustainable development, circularity and decoupled economy are being researched. As Jensen et al. (2011) conclusively observed there is an intensified interest to promote the reorganization of environmentally damaging and resource-wasteful anthropogenic industrial systems into environmental friendly and resource-conservative ones.

A series of methods, including their variations and combinations, assess material and energy flows and stocks of raw materials and goods in processes at different scales under the scope of IE. These methods are based on the system under investigation which can be a product or a material within a process or a region. Thus, they can be defined as product-oriented and material -oriented methods. Product-oriented methods study products and its effects with the environment, such as Life Cycle Assessment (LCA) (ISO, 2006) and Material Input per Service Unit (MIPS) (Liedtke et al., 2014). Material-oriented methods conform a broader spectrum and are suitable for the analysis of processes or geographical regions like Environmental Input-Output Analysis (EIO) (Tukker and Jansen, 2006), Waste Input-Output Analysis (WIO) (Nakamura et al., 2007), Ecological Footprint Analysis (EFA) (von Gleich and Gößling-Reisemann, 2008), Material Flow Analysis (MFA) (Brunner and Rechberger, 2004) and Substance Flow Analysis (SFA) (van der Voet, 2002). A further classification group is the monetary-oriented methods for IE applications, which are Input-Output Analysis (IO), Life Cycle Costing (LCC) and Cost-Benefit Analysis (CBA), but because of the scope and objectives of this work they will not be discussed further.

Within these methods, common fundamental principles are kept: (1) to understand and assess material and energetic exchange, flows and accumulation (2) to create connections between the environment and human activities, and (3) to identify potential environmental impacts inherent to the system. In fact, methodological over-lapping takes place, allowing synergistic applications in products, industrial processes and geographical regions. The methods have advantages and shortcomings, but they all prove, however, to be adequate tools for (1) metabolic quantification and qualification of materials, goods and substances within a system in physical or monetary metrics, (2) interpreting the effects of anthropogenic activities on nature and resource extraction and disposal, and (3) to highlight and recognize strategies in reducing or coping with environmental impacts.

LCA points out environmental impacts and is used for improvement potentials of manufacturing processes. With the selection of a relevant functional unit and category indicators, a quantifiable representation of environmental issues of concern and performance can be evaluated for decision- making and improvement of material and energy efficiency or reduction of pollution loads during the whole product's lifetime (ISO, 2006; Kissinger and Rees, 2010). The versatility of LCA also allows a thorough quantification of material and energy flows within a system boundary. Notwithstanding, the static nature hinders the incorporation and development of stocks. Because of the goals of this method, a thorough study of a dynamic multi-material system is not possible as it cannot answer the types of questions intended in this work. The LCI is however, a useful step in evaluating AMS as it provides information about the material and energy inputs and outputs for many processes and products. The MIPS method takes into account direct and indirect material use as well as used and unused extraction and focuses on the resource level and material input inside a system to determine several environmental indicators under a static fashion (Ritthoff et al., 2002). Some of the MIPS indicators might be useful for characterizing an AMS; nevertheless, it shows pitfalls in describing a complete system in the antroposphere, where manufacturing, consumption and waste treatment processes take place.

About the material-oriented methods, the Environmental Input-Output Analysis (EIO) estimates materials and energy inputs, and environmental emissions outputs from economic activities at different scales. In high level of aggregation (at an industrial level, for example) it combines economic data of input-output tables (IOT) with Physical Input-Output Tables (PIOT) of resource use or emissions, to allow monetary values link to physical accounting and environmental costs, such as externalities (Tukker and Jansen, 2006; Kissinger and Rees, 2010; Jungbluth et al., 2011). A main drawback of this method is the difficulty of construction of dynamic IO models, which have been rather extensions of static IO models, and presents a challenge for models based only on empirical data and physical flow statistics (Lennox and Turner, 2009). This limits the capacity of investigating parameters like stock building and changes in consumption patterns. Additional variations have been developed such as the Multi-regional Input-Output Analysis (MRIO) or the Waste Input-Output Analysis (WIO). The former combines various economies in one single IO matrix to evaluate regional and international inflows and outflows, based on allocation parameters within the different processes and regions (Peters and Hertwich, 2009). The latter incorporates a material composition matrix to estimated IO data of waste and scrap (Nakamura et al., 2007). The Ecological Footprint Anaylsis (EFA) translate requirements to produce resources and absorb wastes of a population in terms of real (or virtual) land- and water-use hectares (von Gleich and Gößling-Reisemann, 2008) necessary to sustainable support a specific region (Gößling-Reisemann, 2008). Thus, it becomes more an indicator to determine the environmental and biophysical burden or stress an agent, such as population or industrial processes, imposes on its supportive ecosystem. One last method is the Material Flow Analysis (MFA) with assess systematically material and energy balances with the aim of distributing and allocate materials in a quantitative way (Bringezu et al., 2003; Brunner and Rechberger, 2004). This method is widely used at economy-wide levels but it is capable of evaluating macro-, meso- and micro-scale systems in a static or dynamic perspective. For the study of dynamic material systems the MFA method is very useful at anthropogenic socioeconomic metabolism analyses.

Table 1 summarizes the main features of each discussed method and illustrates the range and applicability of these. From the above-mentioned methods not all are appropriate for the study of economy-wide carbon-based material systems in the anthroposphere. Despite the wide reach and versatility of the discussed methods for analysis and description of environmental issues, the MFA/SFA method is the most appropriate and indicated method for the interest and objectives of this work. Without discussion, it is the most suitable for the purpose of this work as it has the capacity to evaluate relevant variables of SEM required to understand and model AMS. A full description of the method is given below.

Table 1: Reach of the methods used for evaluation of socioeconomic metabolism (SEM)

| Method | Re-source volumes | Manu-fac-turing | Product market | Waste market | Final use phase | Waste treat-ment process | Emis-sion volumes | Dyna-mic |
|---|---|---|---|---|---|---|---|---|
| LCA[a)] | X | X | - | - | X | X | X | - |
| MIPS[b)] | X | - | - | - | - | - | X | - |
| EIO[c)] | X’ | X’ | X’ | - | - | X | X | - |
| EFA[d)] | X | - | X | - | - | - | X | - |
| MFA[e)]/SFA[f)] | X | X | X | X | X | X | X | X |
| WIO[g)] | - | X | X | X | X | X | X | - |

*Comments:* LCA: Life Cycle Analysis; MIPS: Material Input per Service Unit; EIO: Environmental Extended Input-Output; EFA: Ecological Footprint Analysis; MFA/SFA: Material/Substance Flow Analysis; WOI: Waste Input-Output Analysis; (*) indicates monetary terms; (’) indicates monetary and physical terms. *Sources:* [a)](ISO, 2006); [b)](Liedtke et al., 2014); [c)](Tukker and Jansen, 2006); [d)](von Gleich and Gößling-Reisemann, 2008); [e)](Brunner and Rechberger, 2004); [f)](van der Voet, 2002); [g)](Nakamura et al., 2007).

Finally, the family of methods and developed models all describe different aspects of SEM. Combinations and further developments generate extended or hybrid methods according to research interests and purpose. As mentioned, the methods allow physical-physical, physical-monetary, monetary-monetary combinations to improve analytical capacities and reduce the specific limitations each method has. Some examples are described below. The LCA inventory analysis step can be established through a MFA. Here, the LCA can change from a product-oriented problem to a wider system analysis (Brunner and Rechberger, 2004). Conversely, MFA results can be evaluated with LCA impact assessments to define environmental indicators, as well as by EFA (von Gleich and Gößling-Reisemann, 2008). Further, the input-oriented concept in MIPS is very compatible to the output-oriented LCA; in many cases the service unit of MIPS is the same functional unit of LCA (Liedtke et al., 2014). MIPS can be applied to mass balancing in MFA at macro-level assessments (Brunner and Rechberger, 2004). Further development of the EIO has been made, for example, by LCA practitioners, creating the so-called hybrid LCAs (Jungbluth et al., 2011) or used in EFA studies (Turner et al., 2007; Wiedmann et al., 2007). Monetary IO tables are easily converted into Physical IO tables to obtain material composition of products (Nakamura et al., 2007). In some studies, the allocation of raw materials in the manufactured goods followed input-output (IO) models and used life cycle inventory (LCI) data (Hischier, 2007), in LCA studies (Pauliuk et al., 2015b) or in MFA studies (Nakamura et al., 2007). As one last example, data originated from MFA/LCA in EFA studies, mostly at local or specific products scale, is used to estimate the overall size of the footprint (von Gleich and Gößling-Reisemann, 2008).

## 2.3. Material Flow Analysis (MFA)

The MFA method is a systematic assessment approach of material and energy balances within complex systems to distribute, allocate and accumulate materials and resources of processes and activities in a defined spatial-temporal dimension and it is one of the most widely accepted methods for modeling flows, stocks and processes. Following the principles of the law of mass conservation, the method can be controlled by comparing all material and energy inputs, stocks and outputs, making it an attractive decision-support tool in resource, waste, and environmental management in anthropogenic systems (Bringezu et al., 2003; Brunner and Rechberger, 2004). The method is also known as Material Flow Accounting, as it keeps track of flows and stocks (EC, 2001; Bringezu et al., 2003; Hinterberger et al., 2003; Weber-Blaschke and Faulstich, 2003; EUROSTAT, 2013). The versatility of the method permits the evaluation of material, substances and elements (Chen and Graedel, 2012). For example, analyses of strategic metals like copper scraps (Daigo et al., 2009), worldwide lithium availability (Schebek et al., 2015), aluminum flows and stocks (Buchner et al., 2015) among many others have been performed in form of raw materials or finished goods for global or national markets (Giljum et al., 2014). Even further, some authors (van der Voet, 2002; Månsson et al., 2009; Bollinger et al., 2012) define this former analysis as Substance Flow Analysis (SFA). These analyses range from households to the entire globe, covering enterprises and businesses, regional and national boundaries.

As discussed in chapter 1, at the anthropogenic level, human activities determine courses of action and should be measured and evaluated to call for attention (if necessary) about the effects in the anthroposphere and surrounding ecosystems. The multi-scale versatility of MFA allows the study of different type of systems. In this sense, according to Baccini and Brunner (2012), three types of systems of growing complexity can be defined. A material system links processes, flows and stocks through material flows. If energy flows are included, it is referred as metabolic system. Finally, the anthropogenic system considers, additionally, financial and information components or levels. The main focus in this work resides in the first system level in the anthroposphere.

Despite the lack of a standardized procedure to perform MFA studies (Baccini and Brunner, 2012), a general procedure of the methods is shown in figure 1 that encloses the main methodological modeling steps and depicts its solving process. These steps are, similar to LCA, (1) goal and scope definition, (2) inventory, (3) modeling, (4) and finally interpretation. The presented procedure is not the unique approach. MFA is widely applied in domains of environmental management considering several options in three main components of the general modeling structure of the stock-flow systems: (1) time-dependency: determines if the model is static or dynamic, (2) stock dynamics approach: defines if stocks are modeled with a top-down or bottom-up approach, and (3) perspective: sets the model flows and stocks in a retrospective or prospective time frame (Müller et al., 2014). In many cases both components are combined.

The modeling of material systems in the anthroposphere provides insight in the determination of waste generation, stock building and raw material requirements, as well as information about the societal metabolism to develop strategies for material circularity. Despite the different possibilities for system categorization, stock-flow modeling share common structures that can be replicated and generalized within the modeling scales. Therefore, for the study of dynamics of material systems in the anthroposphere under environmental and techno-economic interactions and because of the nature and goal of this work, the MFA method is the most suitable to describe, evaluate and estimate the behavior of carbon-based products and final goods in a region under a SEM perspective. The holistic approach of MFA and its synergistic characteristics to combine advantages from the other discussed methods sets an absolute and clear framework for the study proposed here. Because of the versatility and flexibility of the MFA method, several components can be included. Here these are defined as: (1) environmental and (2) sociotechnical components of MFA modeling. The former component focuses on the analysis of resource demand, waste generation and emissions to the environment. The latter evaluates manufacturing efficiencies, waste recovery rates, consumption patterns and innovation in related technologies.

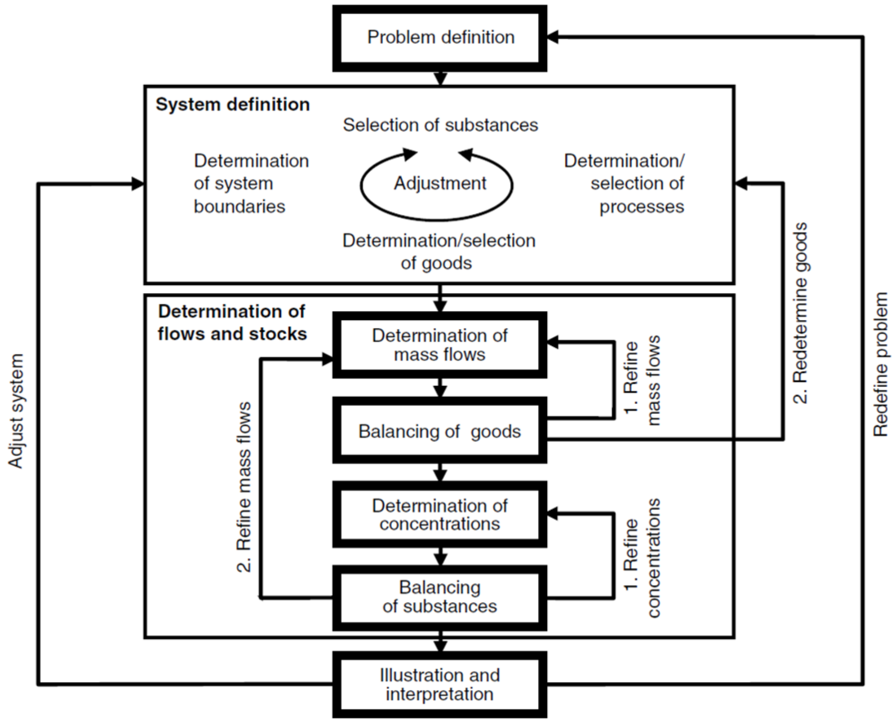


Figure 1. General step-approach for MFA method according to Brunner and Rechberger (2004)

## 2.4. SEM approach for economy-wide material systems

The study and understanding of AMS at an economy-wide perspective using mathematical based modeling offers extended possibilities and advantages at the research level in both retrospective and prospective views (EC, 2001; EUROSTAT, 2013; Fischer-Kowalski et al., 2011; Giljum et al., 2014). An economy-wide view of the material system (material flows of a whole national economy) is illustrated in figure 2. This approach gives a comprehensive representation of the main components of a stock-flow model in societal metabolism. Such general approach has the highest level of aggregation and it conceptually provides information on the composition and metabolic performance of an economy or a socioeconomic system (Fischer-Kowalski et al., 2011), mostly through input and output environmental indicators like "total material requirements" (TMR), "direct material input" (DMI) or "domestic processed output" (DMO), among others (Bringezu et al., 2003; Fischer-Kowalski et al., 2011). In figure 2 the national economy system is divided in the anthropogenic and the biogenic system. Primary resources are supplied either from the biogenic system or from foreign markets, with the exception of water and air. Similarly, domestic outputs are discarded in the biogenic system, exported and part of this flows become secondary raw materials. The domestic outputs include emissions to the atmosphere. As a result of these flows, stocks are added on both systems, although governed by different driving factors. At the economy-wide level, hidden flows are materials extracted or used in the processes of obtaining the inputs relevant flows used in the national economy, but unfortunately are not accounted in the overall balance. For example, in mining activities it creates a large environmental burden limiting the reach and effectiveness of an economy-wide stock-flow model (EW-SFM) analysis.

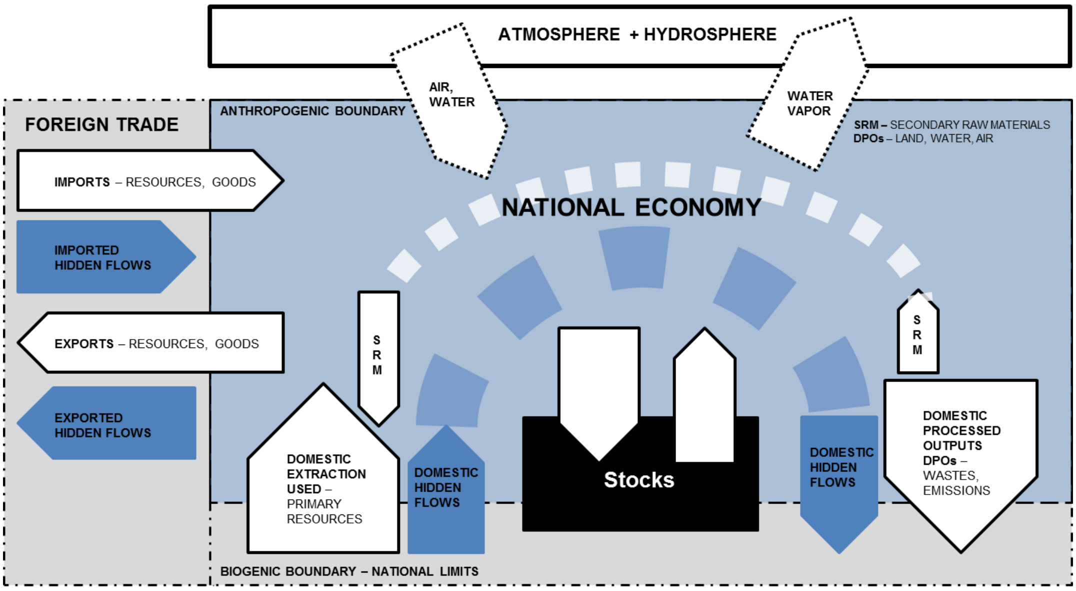


Figure 2: Economy-wide stock-flow perspective for material systems

Finally, the SEM in economy-wide AMS are described as the set of flows, stocks and processes of specific materials necessary to fulfil a particular basic human need and defined as activities. Activities include the actions of nourishing, hygiene, health, leisure, transportation, communication, protection, work, among others (Brunner and Rechberger, 2004) and they cover both biological-driven and socioeconomic-driven needs in the anthroposphere. Activities become one of the modeling pillars for most anthropogenic systems (Bringezu, 2003). Part of the environmental challenges and threats that humankind has confronted in the last half-century are the result of the speed up of industrial and manufacturing processes, the improvement of living standards, and the high rates of consumption of goods and use of physical services with such materials; all in all the satisfaction of anthropogenic activities (Pauliuk and Müller, 2014). Sometimes one material or good can fulfil several activities. For example paper is part of the activities of communication, nourishment, health and leisure. The materialization of activities is made through goods that provide a service. Because services are time-dependent and highly specific, modeling the dynamics of the AMS under the service perspective enables a broad and complete approach and understanding of the behavior of the system.

# 3. A model for dynamic material systems in the anthroposphere

## 3.1. Background for an economy-wide MFA-based dynamic stock-flow model

The requirements and protection of finite and renewable resources, the rational waste management of discarded post-industrial and post-consumer outflows and the strategies to cope potential sources of carbon emissions are forthcoming measures that should be studied and addressed under a stock-flow analysis. In this analysis, carbon flow and stocks modeling provides a scientific background for understanding carbon-based material systems in the anthroposphere and highlights the attention it should be driven to the potential and concurrent danger of $CO_2$ emissions originated not only from flows but also from stocks in air, water and land. Based on these two main percepts, a dynamic stock-flow model is proposed to evaluate the behavior of material systems in the anthroposphere and specifically the behavior of stocks and flows from carbon-based materials. The current discussed dynamic model presented in this chapter complies strongly in structure and logic with a previous developed carbon flow model for regional analysis. Uihlein et al. (2007) proposed an IO-based model to identify carbon sources and sinks and define a carbon inventory in Germany, under the name of CarboMoG as it is discussed as follows.

### 3.1.1. Carbon Flow Model of Germany (CarboMoG)

The interest of evaluating carbon-based materials in material systems in the past have been materialized in the development of various local models. Uihlein et al. (2007) developed the IO-based static model Carbon Flow Model of Germany (CarboMoG) to identify carbon sources and sinks in this region. As its name suggests, the model focused on the analysis of carbon flows and presented a comprehensive analysis of the carbon material and energy system and inventory.

This comprehensive IO model analyzed in-depth regional flows for rational carbon management. With the estimation of carbon flows along the different economic sectors within the whole German economy, from the harvest of wood or agricultural products to discard of wastes and emissions, the model provided a regional material and energy snapshot, in terms of carbon. It considered both biogenic and anthropogenic carbon flows and a rudimentary estimation of stocks. Thus, the model provided a sound base for understanding the nature of flows within the German boundaries, but lacked in a profound description and comprehension of the behaviour of anthropogenic stocks. The estimation of biogenic carbon stocks (renewable stocks, and specially wood) has been widely discussed in other models with comprehensive results (Weimar, 2013; Mantau et al., 2010a) but a detailed study of the behavior of anthropogenic stocks is still in nascent stages.

Besides the shortcoming in the detailed estimation of carbon stocks, the static approach presented a drawback in the modeling of dynamic flows for specific time periods. As any IO-based model, it provided detailed results for one specific time period and proved to be an adequate basis for future in-depth analysis of rational carbon management or analysis of carbon pools and carbon stocks changes (Uihlein et al., 2006). Nevertheless, the very limited description and modeling of the dynamic behavior of carbon stocks and flows, showed a pitfall and a strong potential for developing a economy-wide MFA-based stock-flow model, where a detailed dynamic behavior of the anthropogenic stocks and flows could be thoroughly studied. With the static characteristics of CarboMoG, the model lacked the possibility to research environmental topics such as future generation of wastes and emissions, evaluation of material cycles, estimation of demand of natural and anthropogenic resources or understanding of the dynamics of a sustainable SEM perspective. This dynamic behavior is a major topic of research and environmental concern for several reasons: it enables (1) a prospective approach of the material systems development to visualize possible bottlenecks or challenges, like management and generation of wastes, (2) evaluation of material cycles, (3) conservation of natural and anthropogenic resources, and (4) creation of a framework for evaluation of circularity. All with urgent needs of research. Further, dynamic models provide a sound base for pertinent estimation of stocks and understanding its behavior.

The special focus on carbon flow and stocks modeling highlights the necessary attention it should be driven to the potential and concurrent danger of the $CO_2$ emissions originated not only from flows but also from stocks on climate change, and to provide a scientific background for understanding carbon-based material systems. Based on these two main bases, an economy-wide dynamic stock-flow model is proposed to evaluate the behavior of material systems in the anthroposphere and specifically the development of material carbon flows and stocks, its impact and effects in the society and in the environment.

### 3.1.2. Consumption-oriented vs stock-oriented modeling

The starting point for the modeling of an AMS is the fulfilment or satisfaction of human needs through services. Notwithstanding, to achieve this purpose the relationship between flows and stocks is approached by two perspectives, namely a consumption-oriented approach (Kleijn et al., 2000; Hashimoto et al., 2004; Elshkaki et al., 2005; Schaffartzik et al., 2014), which evaluates the per capita consumption of a material required to provide a service; or a stock-oriented approach (Binder et al., 2001; Müller, 2006; Bergsdal et al., 2007; Hu et al., 2010b) that evaluates the per capita stock of material required to provide a service. Consumption-driven models estimate amounts of input and output flows over time and determines stock building. Conversely, stock-driven models estimate change in stocks over time and defines values of both inflows and outflows. In other words, the first approach states that domestic demand is a driving force of the national economy as humans consume goods to fulfil needs provided through a service and this leads to the accumulation of material or stock building. The second approach contemplates the human requirements for a specific stock of a service for the satisfaction of needs and that this need drives the demand and thus the manufacturing of goods. Both approaches have been extensively used in various research environmental fields, with a clear preference for the first approach of nearly nine of ten cases (Müller et al., 2014). Flow-driven models are also seen as top-down approaches and stock-driven as bottom-up. Neither of these approaches could be defined as better, but they are dependent of the aim and research objective of every case. Although, bottom-up approaches are currently not as often used as top-down approaches, it could provide important attention on consumer behavior as it has strong influence in the product lifetime or the disposal pathways, and in sociocultural and spatial differences in patterns of use (Müller et al., 2014). This shows that the modeling approach of EW-SFM is a chicken-egg dilemma. There is no right or wrong approach and both have positive and negative things. For example, the stock-driven model is clearly described by Pauliuk (2013) as follows: “for several of these physical services, it is the in-use stock of products and materials, rather than their annual consumption flow that provides service to the end-users. The consumption of products and materials is not an end in itself, but serves the purpose of building up or maintaining in-use stocks, which are used throughout the lifetime of the products. One can say that in-use stocks bridge the gap between service and consumption". This indicates, however, that the required level of stocks that satisfies a need must be defined and in most cases it is defined the developed world standards are the required levels. This perspective may be in some cases perverse in the sense that if the developing world has this goal for saturation point, it will mean an overuse and depletion of natural resources around the globe.

As this model is studying a developed country, where saturation levels are practically reached, the future of such societies in perspective of circularity and sustainability is based mostly on the change of consumption patterns and technological innovation, given an noticeable advantage to the consumption-driven approach. The service approach to satisfy needs is based on the changes in per capita consumption. For models where saturation points are expected and a not everlasting growth in consumption, per capita consumption can be describe mathematically precisely with logistic curves. Additionally, because consumption patterns changes can be modeled with better precision and because of the lack of knowledge about several stock values of the evaluated materials and products, for this model the approach "per capita consumption of a material required to provide a service" will be adopted.

Combining the conceptual structure of CarboMoG with a dynamic MFA approach and the above-stated research interests, an economy-wide MFA-based dynamic stock-flow model (EW-SFM) is developed to study the behavior of material systems under environmental and sociotechnical frameworks within a spatial-temporal boundary. These types of evaluations anticipate depletion of resources, bring awareness of future situations, and identify unknown flows with impact and effects in the society and in the environment. The model presented in this chapter is a generalized approach of an EW-SFM, to highlight the potential and versatility of the model for studying other material systems besides carbon. Nevertheless, the main focus is carbon-based stocks and flows, as it will be discussed thoroughly in chapter 4. Under a consumption-driven approach the presented model estimates material flows and stocks of raw materials, goods and wastes within a material system in the anthroposphere. The model structure and conceptual framework is fully explained below.

## 3.2. Model structure, scaling and dynamics

The AMS is a socio-economical construct undermined with technical and environmental influences, which final goal is the procurement of satisfaction of human needs through services provided by final goods, using natural and anthropogenic resources. The conceptual framework can be expressed through an interconnected network of material flows, stocks and sectors for modeling material systems in the anthroposphere. The modeling and stock-flow analysis within an economy-wide approach is based on a proper model structure, as illustrated in figure 3 that identifies pertinent interrelated sectors or processes within accurate system boundaries. A process can be defined as the event where material and energy are transformed, manipulated, transported, aggregated, distributed or depleted, or any combination of these, where material and energy balances are fulfilled. The system boundary encircles the analyzed system with a convenient space and time definition to fulfil the research interests of the system under investigation. Models do not represent or reproduce an exact replica of the system under investigation, but under the correct level of granularity it captures the objectives and questions wished to be answered. The system under investigation is composed of the processes or phenomena necessary to perform any form of behavior in a dynamic or static way. Here, the term dynamic must be defined as it may have several definitions within the modeling approach. For some dynamic represent a non-linear model with feedback and causal loops that define the final state of the system according to the dynamic response of these loops. For others, the term dynamic represents a model that contains the variable time in the system. Under time constrains a system becomes a dynamic system, where as in case no time is present it is referred as static system. The dynamism of the model discussed in this work corresponds to the second definition. Additionally, modeling is an information-based process, with high data quality requirements. It is desired to obtain precise, complete and representative data to minimize data gaps and the uncertainty of the results. For an economy-wide material systems modeling national limits and annual time slots are mostly preferred. The general model equation is described with equation (A.1) shown in Annex A.

From figure 2, two main system boundaries for the modeling of material systems in the anthroposphere coexist: the anthropogenic boundary (dark shaded area in figure 3) and the biogenic boundary (lower light shaded area in figure 3). The anthropogenic boundary is described by main activities realized at a sociotechnical (urban/rural) level and includes broadly manufacturing of products, commercialization, consumption and waste treatment of discarded goods with material and energy use.

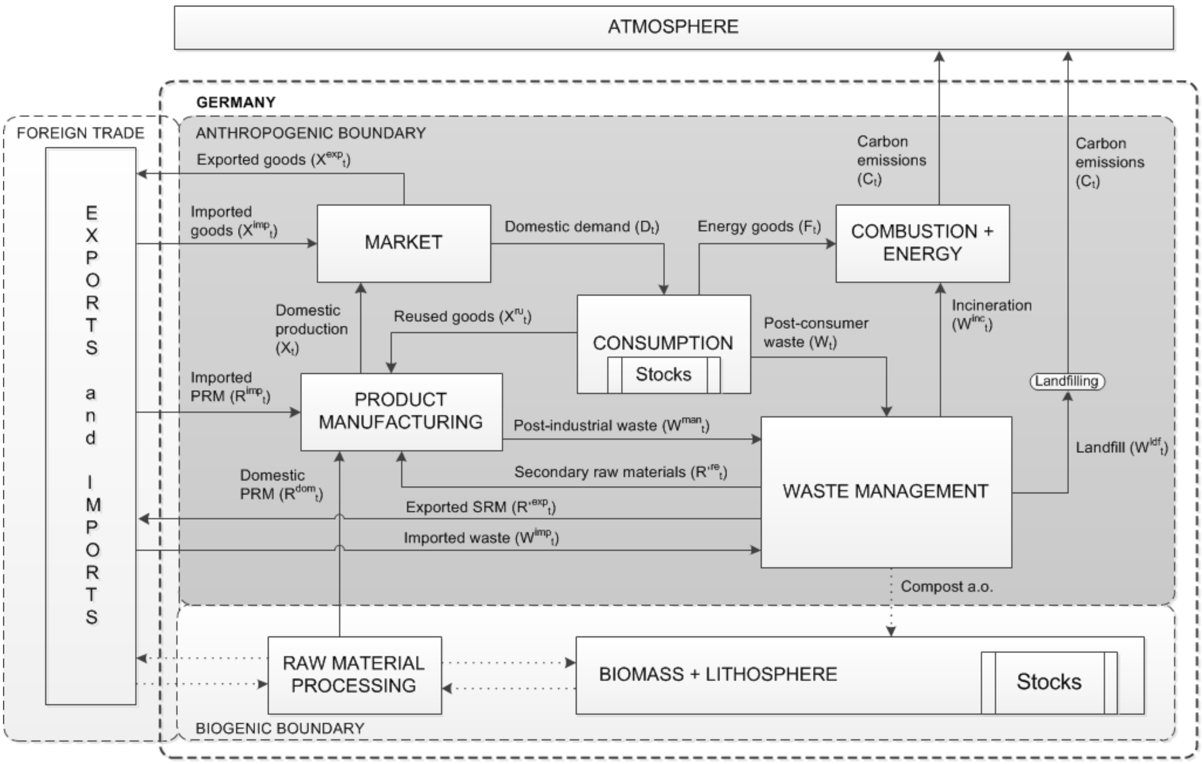


Figure 3: General model structure of the developed EW-SFM for material systems in the anthroposphere. *Comments:* dotted lines are ignored flows; a.o.=among others.

The biogenic boundary includes mainly activities at a natural level with reduced sociotechnical (non-urban/non-rural) influence. Despite its name, within the biogenic boundary abiotic materials such as lime or crude oil are present. Also the transition sector "raw material processing" was situated within this boundary because of the defined raw material requirements at the manufacturing sector. In the "raw material processing" sector biotic and abiotic primary raw materials are extracted, harvested and transformed to processed raw materials for the industry. For example, harvested wood is turned into sawnwood and other semi-finished wood products or crude oil is transformed into polymers or rubber; these manipulated materials are considered the input flow for the anthropogenic boundary. The interest of the model relies on the anthropogenic stocks and flows which use processed raw materials for the manufacturing of final goods. This boundary differentiation is proposed to define and highlight a proper setting for the evaluated anthropogenic boundary.

Most of the anthropogenic and biogenic activities can be clearly differentiated. Manufacturing processes, trade and use of goods, discard of commodities, waste treatment processes and the multiple services for the satisfaction of needs (human-prioritized activities) are strongly located inside the anthropogenic boundary. Non-human-centered areas like natural protected regions, carbon assimilation or lithospheric resource reservoirs are found inside the biogenic boundary. This can be true; however, a solid dividing line between both systems cannot be traced. Activities such as recreation, air travel or electricity generation in power plants uses both systems simultaneously. Also, soil, water and air and the growth of biomass are found in both systems. The combination of the anthropogenic and biogenic systems forms a complete economy and defines a larger external system boundary, which in this case matches the political limits. Further, as an open-type system a permanent exchange of material and energy happens across its boundaries (both internal and external), that is, flows of material and energy takes place between the anthroposphere and the natural system, as well as between the economies. Thus, a third system named foreign trade (left light shaded area in figure 3) is required and shared by both, the anthropogenic and the biogenic boundaries, to indicate material sinks and sources located outside the political borders.

With this delimitation and combination of system boundaries, the model structure can be consistently described. The dynamic stock-flow model within the anthropogenic boundary is composed of five interconnected sectors containing a series of processes to represent the anthropogenic structure under an economy-wide approach. Each sector must comply and fulfil mass balance equations, which are mathematically expressed in Annex A. Corresponding inflows and outflows, and if available, the changes in stocks over time, define each sector, which are connected through material flows that link the anthropogenic system to the biogenic system and the foreign trade.

Outside of the anthropogenic system three sectors are present: (1) biomass and lithosphere with renewable and finite resources, (2) raw material processing and (3) foreign trade of goods, semi-finished products and raw materials. As discussed previously, the first sector provides primary raw materials (oil or wood) coming from lithospheric or superficial sources by extractive or harvesting processes. The second sector processes and prepares these raw materials in semi-finished goods (such as wood-engineered panels or sawnwood) or processed raw materials (polymer pellets, synthetic rubber) for use in the manufacturing sector. The third sector corresponds to the foreign trade system.

### 3.2.1. Hierarchical model scaling

Modeling anthropogenic materials systems requires the analysis of economic, social and environmental aspects. Some authors have suggested the analysis of the system in separated hierarchical layers like service layer, final product layer, material layer, energy layer and emissions layer (Pauliuk, 2013). In the analysis of material systems such categorization might increase the complexity and provide limited further systemic advantages. Initially, this model can be expressed in just three layers: services, materials and energy. Energy can be evaluated either from an exergetic approach or from a material flow in-use perspective for example in terms of heating or transportation. This means a quantification of the material energy carriers in terms of mass and not of the energy content per se. In this sense, the energy goods become part of the material level. Therefore, the main layers to evaluate the societal metabolism for AMS are the service and material level.

A service is the provided benefit given by a final good for the satisfaction of a human need or activity. Therefore, services of packaging, communication, transportation, protection (built environments and infrastructure), well-being among others, require materials like metals, wood, plastic or paper. These are known as material groups. Within the material groups a further specification of the service provided is given by a clear product group. For example, in the service of packaging product groups like bags, boxes, pallets or drums are found. In the service of communication printed material or electronic appliances are discriminated. Similar arrangements are found in the other services. Finally, the use of the product groups is governed by an in-use lifetime that can range from some days to decades, which is a combination of the product quality, use and consumer behavior.

The analysis of the material level includes the final product for material or energy uses and related emissions within each of the in-use lifetime groups. Now, since a service can be satisfied with different materials, and some products can be manufactured with various materials and in-use lifetimes, an aggregation scale is necessary. Figure 4 illustrates how the model is constructed with a hierarchical scale of services, material groups, product groups and in-use lifetime of products, and the relationship between these different modeling scales. It further provides an overview of the modeling granularity.

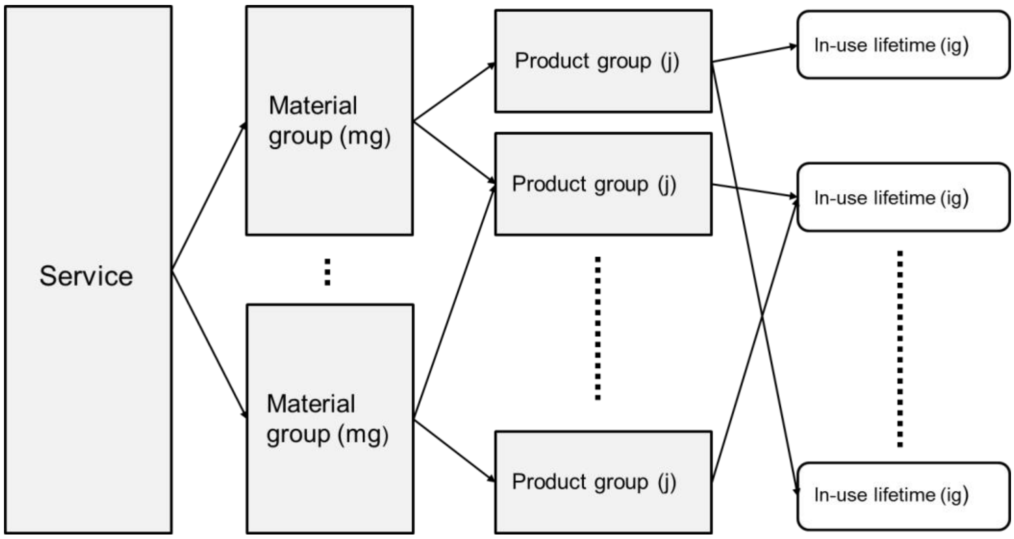


Figure 4: Model hierarchy for services, material groups, product group and in-use lifetimes

### 3.2.2. Model dynamics

With the model flow diagram (see figure 3) and the hierarchical classification (see figure 4), flows and stocks of materials and final goods acquire consistent relationships between the sectors suitable for dynamic modeling at an anthropogenic level. The dynamics of the model are time constraint and are understood as the variation of inflows and outflows within the different sectors and through the system boundaries over periods of time. The dynamics are changes in socio-technical, demographic and environmental aspects, like the dynamics of population, manufacturing efficiencies, changes in in-use lifetime of products, recycling factors, among others. These parameters impacts directly or indirect the demand of primary and secondary raw materials, the consumption of final goods, stocks dynamics, waste generation and related carbon emissions. With a combination of time-dependent and time-independent elements along the simulation, a dynamic algorithm for the model is described in figure 5. This figure shows the main relationships and variables required for model dynamics and potential points change in the material system. The six dynamic variables are: (1) domestic population, (2) foreign population, (3) required materials for services, (4) product groups domestic market shares, (5) in-use lifetime of final goods and (6) product group composition, and they will be described below.

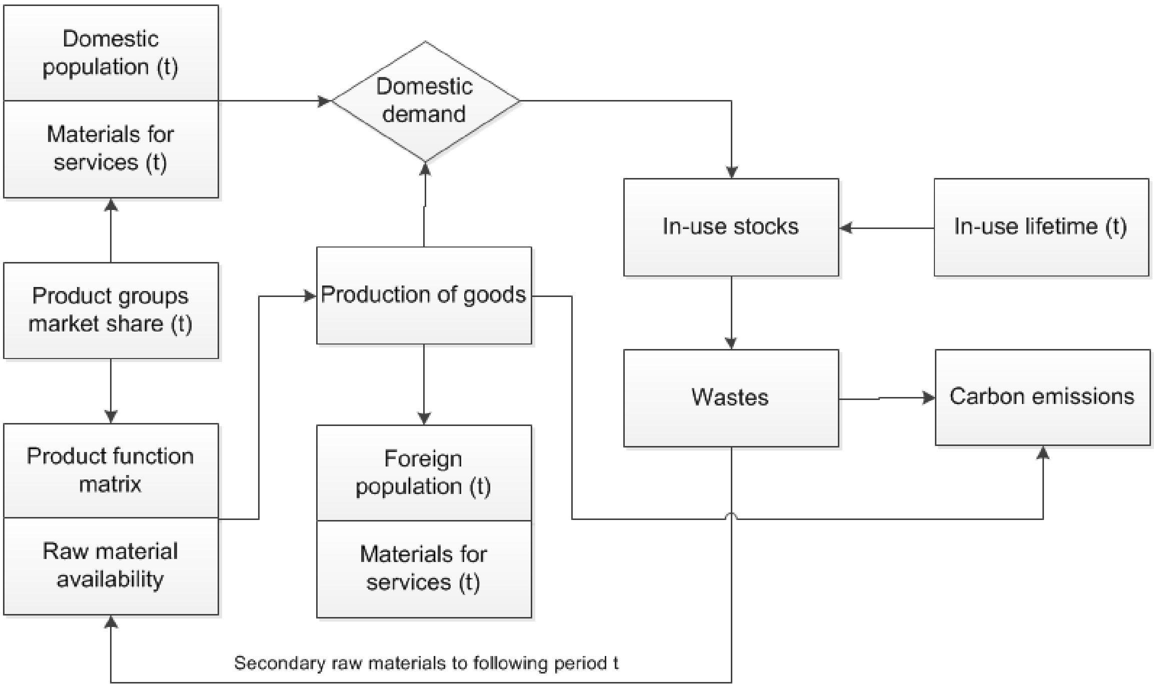


Figure 5: Schematic dynamic modeling algorithm

Population is one of the most relevant dynamic drivers in the anthroposphere, but it has moderate dynamics and only noticeable changes occur after long periods of time. Since needs must be permanently satisfied, population becomes a driving force for consumption flows and material stock building at the domestic and foreign level.  The population in Germany is expected to decline, while the foreign population shows signs of continuous growth (DESTATIS, 2015b; DESTATIS, 2015a). Domestic population drives a domestic demand, while foreign demand does likewise for volumes of exported goods, impacting the product manufacturing sector. A specific amount of materials for the manufacturing of goods are required to provide services that satisfy needs. Because of the changing consumer patterns and choices, some services might be more often needed than others, or even some services might have a trend to disappear along time. This dynamic has a bearing on the volumes of raw materials requirements for the manufacturing of service-related goods, which changes as well the per capita consumption of both services and materials. Further, the variation of the volume of final goods affects proportionally the product group market share, which impacts directly the AMS dynamic. With the annual domestic population stock and the amount of materials required to provide services for the satisfaction of needs, the periodic domestic demand is estimated. On the same line, considering the foreign population and respective need of materials for services, the foreign demand is also calculated. The domestic demand defines the total amount of final goods required per period, which should be provided by the domestic industry and complemented with the import of goods. The foreign population dynamics has a strong influence on the model, especially on market and manufacturing sectors, with the export of materials and goods. Under an AMS perspective, the population stock drives consumption of final goods. Before going further, it is critical a concrete definition of the concept "world population" for the modeling purpose. Assuming the total world population might lead to overrated and unrealistic consumption values. Speaking of the German situation, most of its foreign trade takes place within the European Union. Thus the term "world population" for the model is an estimate of the potential population with purchasing capacity for German products. This assumption will be discussed in detail in section 3.3.2. Both historic and estimated developments of population dynamics are retrieved from the literature; either from statistical databases or comprehensive studies of population developments for regional and world populations (FAO, 2015; DESTATIS, 2015b).

With the information of the product composition and the available primary and secondary raw materials a wide range of manufactured final goods and products satisfy the annual demand requirements. The final volumes of primary raw materials are then adjusted (through an iterative process) to the needs and the availability of secondary raw materials. Once the final domestic demands volumes are estimated through the market sector final products goods are provided for consumption. As shown in figure 4, each product group has a characteristic in-use lifetime, discussed in detail in section 3.3.3. These values are dynamic and its change signifies longer or shorter periods of use before discard. The possibility of choice from consumers, to extend or shorten the use of a product, has an influence in the wastes, stocks and carbon emissions dynamics. Such changes also impact the per capita consumption and market share as more or less products are required for each period. Here, the difference between the flow of goods for consumption and the volume of discarded wastes define the stock dynamics as the remaining volume at the consumption sector. These in-use stocks will eventually also turn into wastes in future periods which will be treated under different waste treatment processes. For the sake of the model dynamics, the recycling and incineration processes are meaningful. The volumes of recovered and recycled post-consumer wastes, or secondary raw materials, are the binding element within the dynamic modeling along the periods, which are used in the immediately following modeling period after its processing. In other words, it creates a permanent dynamic feedback in the AMS that alters the distribution and required volumes of primary raw materials for manufacturing processes.

A further environmental aspect is the carbon-related emissions from the material system. These emissions do not concentrate on energy-related emissions, caused by manufacturing or electricity generation processes, but rather on the potential emissions that carbon-based materials contain. Thus, the emissions are coming from the discarded stocks and used mostly in incineration processes with energy or non-energy recovery. The general dynamic and conceptual structure of the model was clearly presented. Now, each of the sectors will be thoroughly described.

## 3.3. Sectors in economy-wide anthropogenic material systems

Similarly to the model system boundaries, every sector within the material system in the anthroposphere is characterized by specific mass balance equations and activities. The product manufacturing sector balances mass flows between primary and secondary raw materials and finished goods for consumption complemented with consumption behavior patterns expressed in the change of in-use lifetime of goods (reuse or refuse of final goods). The market sector models foreign trade flows, manufactured goods and expected domestic demand. In the market sector the development of foreign markets and the changes in worldwide per capita consumption play a significant role in the volume of exported goods. This volume is complemented with the estimated imported goods. The consumption sector is a pivotal sector between the consumption of final goods and waste generation, modeled by a probabilistic approach. Consumption is seen as one main driving force of the model. The waste management sector allocates post-industrial and post-consumer waste outflows into different waste treatment processes. The combustion sector, closely related to the waste treatment sector, estimates the amount of emitted gaseous carbon formed from incineration from solid waste flows from the different waste management processes, as well as the emissions from final goods used for consumer-level energy purposes. The combustion sector does not consider industrial or process-induced emissions. Below a thorough and detailed description of each relevant sector is found.

### 3.3.1. Product manufacturing sector

The production or product manufacturing sector delivers annual production goods and products to satisfy the domestic and export demand using primary and secondary processed raw materials (or semi-finished products) coming from raw material processing sectors both domestic and foreign markets. Because of the multiple product palettes with similar services, products are gathered in particular groups, denominated “product group”. These are a generalization of the delivered service expressed with an average specific raw material composition and determined by the production function coefficient $h_{i,j}$ (Nakamura et al., 2007). For example, products for packaging or for communication fulfill the same service of packaging but one type used chemical pulp as raw material, while the latter a combination of thermoplastics and metals. The coefficients indicate the processed raw material requirements for the manufacturing of one product group unit as shown in table A.9 in Annex A and it is designated as the production function matrix. The production volume for each product group is estimated from the domestic demand, foreign trade (exports and imports) and feedback flows from consumer behaviors (reused goods) and used to calculate the required amount of processed raw materials to satisfy manufacturing needs. The use of primary and secondary raw materials for the manufacturing of goods is based, then, on the production function matrix.

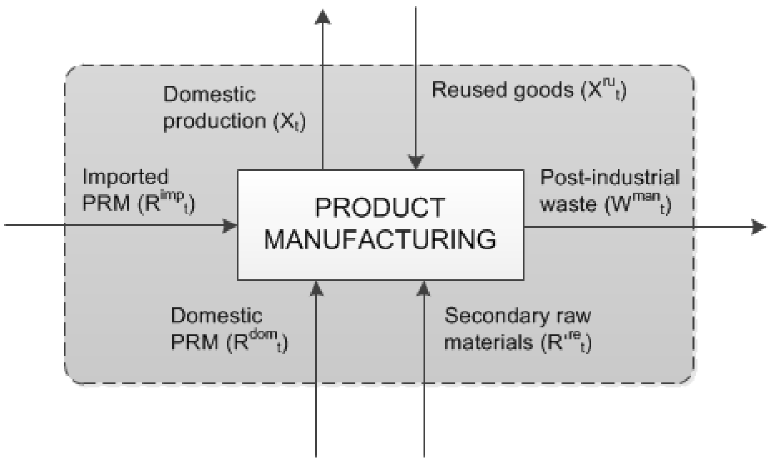


Figure 6: Detailed production sector flows and system boundary

The flows for the product manufacturing sector mass balance are illustrated in figure 6 and expressed mathematically in equation (A.2) in Annex A. This sector considers flows of raw materials, finished goods for consumption, among others. Primary raw materials volumes are complemented with secondary (or recycled) raw material flows; reuse of goods, as a consumption behavior pattern, has an impact over the final production volumes. The model is based on a non-scarce resource concept. It is assumed that abundant resources for the manufacturing of goods are available along the simulation.

It is important to denote that, despite the known environmental effects of the manufacturing industry in terms of carbon emissions, within the study of material systems in the anthroposphere, the emissions generated for energy requirements for industrial operation in the manufacturing process are not considered in the material balance.

### Production function matrix

The calculation of the annual required volume per product group and its raw material requirements is based on an $n \times m$ matrix with $n$ number of raw materials and $m$ number of product groups to solve an $n$-equation system for $m$ product groups (Suh and Huppes, 2005). The matrix is based on the product function coefficients table A.9 found in Annex A. The solution to the $n$-equation system estimates the required processed raw material $R_{i,j,t}$ volumes for the production of final goods. For each product group two equations are used. Equation (1) determines the production volume of goods per product group based on population dynamics, per capita consumption, foreign trade volumes and market share values. Equation (2), calculates the required amount of processed raw materials based on the production function matrix to satisfy the manufacturing needs from equation (1).

$$X_{j,t}^{M} = MS_{j,t}^{mg} \times \left(D_t^{mg} + X_t^{exp,mg} - X_t^{imp,mg}\right) - X_{j,t}^{ru} \;\forall\, m \tag{1}$$

$with,$
$X_{j,t}^{M}$ = $Domestic\ production\ for\ product\ group\ j\ estimated\ with\ flows\ (kt/a)$
$MS_{j,t}^{mg}$ = $Market\ share\ per\ material\ and\ product\ group\ (\%)$
$D_t^{mg}$ = $Domestic\ demand\ of\ each\ material\ group\ (kt/a)$
$X_t^{exp,mg}$ = $Exported\ goods\ from\ each\ material\ group\ (kt/a)$
$X_t^{imp,mg}$ = $Imported\ goods\ of\ each\ material\ group\ (kt/a)$
$X_{j,t}^{ru}$ = $Reused\ or\ refused\ goods\ of\ product\ group\ j\ (kt/a)$
$n$ = $Number\ of\ product\ groups$

$$X_{j,t}^{H} = \sum_{i=1}^{n}\left(\mu_{i,j} \times \frac{h_{i,j}}{\sum h_{i,j}} \times \frac{MS_{j,t}^{mg}}{\eta_{mg}^{man}}\right) \;\forall\, m \tag{2}$$

$with,$
$X_{j,t}^{H}$ = $Domestic\ production\ for\ product\ group\ j\ from\ production\ coefficients\ (kt/a)$
$\mu_{i,j}$ = $Iteration\ value\ (kt/a)$
$h_{i,j}$ = $Production\ function\ coefficient$
$MS_{j,t}^{mg}$ = $Market\ share\ per\ material\ and\ product\ group\ (\%)$
$\eta_{mg}^{man}$ = $Manufacturing\ efficiency\ per\ material\ group\ (\%)$
$m$ = $Number\ of\ product\ groups$

A simultaneous solution for equations (1) and (2) is found for all product groups in each material group fulfilling the restriction of equation (3). Once the solutions are found for all required processed raw materials, the estimated amounts of each raw material used in the whole manufacturing processes are obtained with equation (4).

$$0 = \sum_{j=1}^{m}\left(X_{j,t}^{M} - X_{j,t}^{H}\right) \tag{3}$$

$with,$
$X_{j,t}^{M}$ = $Domestic\ production\ for\ product\ group\ j\ estimated\ with\ flows\ (kt/a)$
$X_{j,t}^{H}$ = $Domestic\ production\ for\ product\ group\ j\ from\ production\ coefficients\ (kt/a)$

$$R_{i,t} = \sum_{j=1}^{m}\left(\mu_{i,j} \times \frac{h_{i,j}}{\sum h_{i,j}} \times \frac{MS_{j,t}^{mg}}{\eta_{mg}^{man}}\right) \;\forall\, n \tag{4}$$

$with,$
$R_{i,t}$ = $Required\ processed\ raw\ material\ i\ for\ period\ t\ (kt/a)$
$\mu_{i,j}$ = $Iteration\ value\ (kt/a)$
$h_{i,j}$ = $Production\ function\ coefficient$
$MS_{j,t}^{mg}$ = $Market\ share\ per\ material\ and\ product\ group\ (\%)$
$\eta_{mg}^{man}$ = $Manufacturing\ efficiency\ per\ material\ group\ (\%)$
$n$ = $Number\ of\ processed\ raw\ materials$

### Manufacturing losses

During the manufacturing process material losses occur as a result of the manufacturing efficiencies. For domestic sources post-industrial wastes or by-products are directed to waste management processes including incineration, landfilling or recycling. In some cases, by-products are used as material input for energy applications. Post-industrial waste is part of the cascade use of materials, but also a source for recycling.

The material losses in the manufacturing processes or post-industrial waste volumes are estimated with manufacturing efficiencies corresponding to each material used. The amounts of manufacturing residues from each raw material are allocated for material uses (recycling, landfilling) or for energy use (incineration) at the waste management sector. The residues volumes are estimated with equation (5). Since leaching effects within the carbon-based materials is negligible, no dissipation in material flows is considered in the model.

$$\boldsymbol{W_{i,t}^{man,\omega} = A_{i,t}^{\omega} \times R_{i,t} \times \left(1 - \eta_{mg}^{man}\right) \forall\, n} \tag{5}$$

$\boldsymbol{with},$

$\boldsymbol{W_{i,t}^{man,\omega}}$ = $\boldsymbol{Manufacturing\ raw\ material\ waste\ to\ waste\ treatment\ processes}$ $(\boldsymbol{kt/a})$

$\boldsymbol{A_{i,t}^{\omega}}$ = $\boldsymbol{Allocation\ factor\ in\ waste\ treatment\ process}$ (%)

$\boldsymbol{R_{i,t}}$ = $\boldsymbol{Required\ processed\ raw\ material\ i\ for\ period\ t}$ $(\boldsymbol{kt/a})$

$\boldsymbol{\eta_{mg}^{man}}$ = $\boldsymbol{Manufacturing\ efficiency\ per\ material\ group}$ (%)

$\boldsymbol{\omega}$ = $\boldsymbol{Waste\ treatment\ process}$

$\boldsymbol{n}$ = $\boldsymbol{Number\ of\ processed\ raw\ materials}$

## 3.3.2. Market sector

This sector balances foreign trade flows (imports and exports of final goods) and manufactured goods to meet the requirements of the calculated domestic demand. Figure 7 describes the sector flows, while equation (A.3) in Annex A describes the mass balance of the market sector, with the above-mentioned variables.

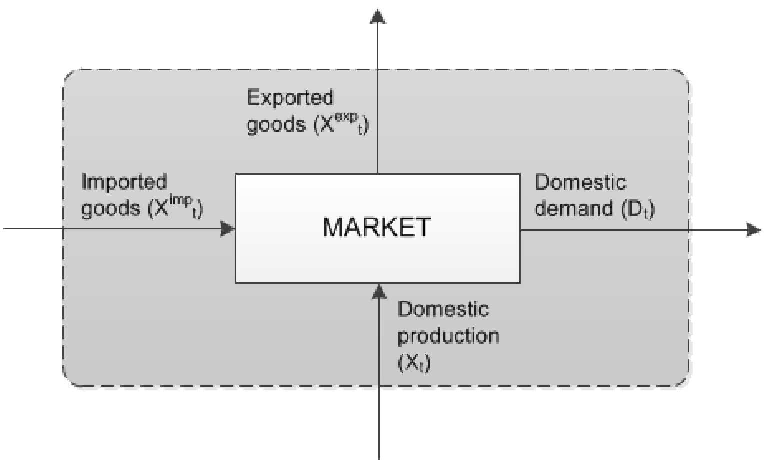


Figure 7: Detailed market sector flows and system boundary

Under the current socioeconomic structures, foreign trades are a crucial part of the development and metabolism of the anthropogenic systems and therefore play a fundamental role in the AMS modeling. The exchange of raw materials, semi-finished and finished products across national borders are main economic activities within current global markets. This sector is susceptible to the development of foreign markets and the changes in foreign per capita consumption, as well as the import capacity of the country, being regulated by the production and manufacturing sectors in terms of raw materials availability and final products demand. At the anthropogenic level, final goods are commercialized for end-user purposes, while raw materials and semi-finished goods are delivered to the manufacturing industries.

Imports provides non-endemic raw materials for the manufacturing of products and also allows the introduction of non-local manufactured products to satisfy consumption needs, which might not be available in the local industries or has a better cost-benefit ratio when produced in other economies. Exports depend on the average world per capita consumption of materials and accessibility of the local industry into foreign markets. As many of the statistical data is compiled in monetary units and not in mass units, the distribution of the import and export flows are based on the domestic market share values of each period. Exports are seen as an economical force that drives not only the financial system, but pushes the innovation and development strategies for new technologies domestically and new markets. In many cases and based on foreign trade policies specific import:export ratios within the economies are expected to be maintained. For the modeling structure, exports and imports flows have been gathered to one single body with the intension of consolidating sources and sinks in one external entity that exchanges the different materials with the anthropogenic system, but it is differentiated by propensity factors for each material. In other words, both import and export flows are independent and driven by different agents closely related to the behavior of consumers. The development of export and import flows is also modeled under a logistic approach. To comply with the consistency of the material system, their trade dynamics are conditioned by behaviors of foreign market (in case of exports) and of domestic demand (in case of imports), as similar as possible under a logistic behavior. The calculation of these two flows within the model is discussed as follows.

### Calculation of import flows

The import of materials in the anthroposphere occurs at the manufacturing, consumption and waste treatment level. Along the different sectors imported flows of primary and processed raw materials, imported goods and imported wastes takes place. All of these have a relevance inside the material system; however, the import of goods play a significant role as they fulfill partially the domestic demand covering to certain degree the satisfaction of needs through material services. Imports are a complementary volume for the manufacturing sector. The imports of primary raw materials are also of great importance to complete missing volumes. For modeling purposes this latter flow becomes not as relevant as the foreign supply for carbon-based materials is assumed to be non-scarce for the modeling period. On the contrary, for the modeling of critical metals or rare earth elements for example, the detailed supply of imported raw materials must be projected.

The amount of imported goods per product group is closely related to the volume of domestic demand, defined by the import propensity factor for each material group. This factor defines the ratio between imported goods and domestic goods in the consumption sector and it is estimated with time-series of imported goods and domestic demand data. For the modeling period, it is assumed it changes at the same rate as domestic markets, as it comply the domestic consumer dynamics. Equation (6) estimates the volumes of imported goods per product group.

$$X_{j,t}^{imp} = D_{j,t} \times IP_t^{mg} \tag{6}$$

*with*,

$X_{j,t}^{imp}$ = *Imported goods per product group* $(kt/a)$

$D_{j,t}$ = *Domestic demand per product group* $(kt/a)$

$IP_t^{mg}$ = *Material group import propensity factor* (%)

**Calculation of export flows**

In the same perspective from import of materials and goods, exports constitute a crucial point of the whole metabolism of the anthropogenic system, which are estimated similarly by data gathering and structuring as the import inflows. An average world per capita consumption is defined for each material group. However for the estimation of exported volumes, a potential trading population is estimated, which, as said above in section 3.3.2., is the potential foreign population with purchasing capacity of German goods. A more specific group with capacity to trade like neighboring countries or countries with free-trade agreements or members of economic trading zones, provide a closer description of the export trade[3]. Almost 60% of the German foreign trade takes place within the EU (WTO, 2015; Stuchtey and Below, 2015). This provides a more realistic value of the active foreign trade population. The value of European population combined with an average foreign per capita consumption values provides a very realistic number of the German economy customers. Assuming a one-to-one consumption of goods from the whole world is rather disproportionate.

Using an export propensity factor of the material groups, estimated as well with time-series data, the final volume of each product group is estimated. Similarly as the estimation of the import curves, the export development along the simulation is based on a logistic curve taking the estimated average foreign per capita consumption parameters, with the aim of simulating the foreign development of the market. The exported goods per product group are calculated with equation (7).

3 The sensitivity analysis showed that the value of the whole world population was extremely sensitive and a small change in the world trade values changed considerably the exported flows. Using such value suggests that every inhabitant of the Earth has the capacity of trading with Germany. This might not be accurate.

$$X_{j,t}^{exp} = PopW_t \times CpCW_t^{mg} \times \kappa_t \times \epsilon_t^{mg} \times MS_{j,t}^{mg} \quad (7)$$

$with$,

$X_{j,t}^{exp}$ = $Exported\ goods\ per\ product\ group\ (kt/a)$

$PopW_t$ = $Trading\ capable\ population\ (million)$

$CpCW_t^{mg}$ = $Average\ foreign\ per\ capita\ consumption\ per\ material\ group\ (kg/cap \cdot a)$

$\kappa_t$ = $Country's\ world\ export\ share$ (%)

$\epsilon_t^{mg}$ = $Material\ group\ export\ propensity\ factor$ (%)

$MS_{j,t}^{mg}$ = $Market\ share\ per\ material\ and\ product\ group$ (%)

The export propensity factor, as well as the import propensity factor, give trade independence to each of the main product groups, and adjusted using historical time series and statistical data. Finally, the market share of the foreign products is assumed to be similar to the domestic market.

### 3.3.3. Consumption sector

In an economy-wide model the consumption of material goods satisfies human needs through a provided service and plays a fundamental role within material flow systems (UNEP, 2010; Jungbluth et al., 2011). It can be regarded as the pivotal or bridging joint between upstream processes (harvesting, raw material processing and manufacturing of goods) and downstream processes (waste management, recovery of secondary raw materials and emissions). At the consumption sector the consumption rate of products is estimated to satisfy demand volumes and estimate post-consumer waste outflows and stock changes. The rate of consumption is driven by the required volume of imported and domestic goods to satisfy societal needs through a provided service and its in-use lifetime. Figure 8 illustrates the consumption sector and its mass balance is described with equation (A.4) in Annex A. This sector includes annual change of anthropogenic stocks, given as the difference between consumed goods (inflow) and discarded goods (outflow) per time period. Outflows are determined by a probability distribution that is linked to the final goods expected in-use lifetimes. Since the in-use lifetime of final goods can be extended or shortened this variable provides the social behavior component to the sector, which is determined as product reuse or product refuse. Both, waste outflow volumes and volume of reused or refused products for material and energy purposes are dependent of consumption patterns. Three fundamental parameters for the modeling of the consumption sector are discussed in detail.

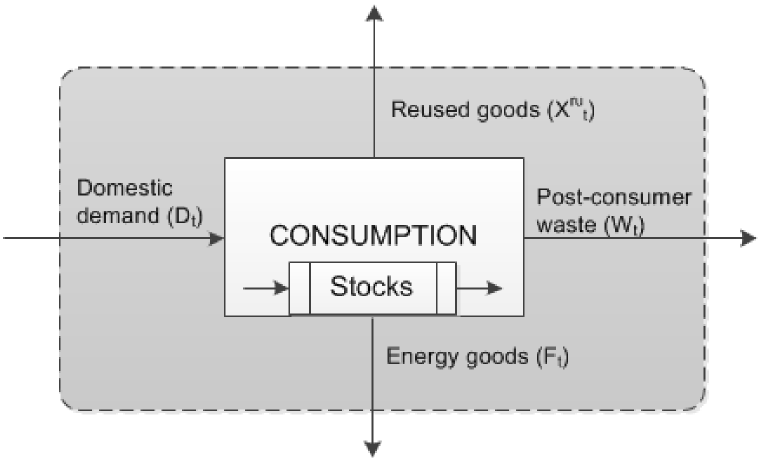


Figure 8: Detailed consumption sector flows and system boundary

### Service-oriented per capita consumption and domestic demand

Services provided from final goods drive the consumption of products expressed in a domestic demand, which influences directly the manufacturing sector. On an economy-wide basis the estimation of per capita consumption, that is, the amount of material required from a product to satisfy a specific service for one individual, gives a solid base for the AMS modeling. A service is an intrinsic property of a product to provide the satisfaction of a human need and it can be delivered by several products. These products can be manufactured with different materials. On the other hand, the fulfillment of the needs is also related to the choice factors of products seen in consumer behaviors. These can range from

Table 2: List of services and products of carbon-based materials

| Service | Material | Products |
|---|---|---|
| Packaging | Paper | Bags, Cardboard boxes |
| | Wood | Pallets, Boxes, Baskets |
| | Plastic | Bags, Films, Containers, Bottles |
| Well-being | Paper | Hygienic paper, special applications |
| | Plastic | Household appliances, residential and non-residential commodities (furniture), medicine objects |
| | Wood | Toys, musical instruments, residential and non-residential commodities (furniture) |
| Heating | Wood | Pellets, fuelwood |
| Communication | Paper | Magazines, newspapers, flyers |
| | Plastic | Telephones, computers, mobiles, tablets |
| Transportation | Plastic | Automotive interior and exterior parts, tires |
| Non-residential buildings | Wood | Panels, windows, floors, doors |
| | Plastic | Windows frames, doors |
| Residential buildings | Wood | Panels, floors, doors, windows, roof frameworks |
| | Plastic | Windows, rugs |
| Infrastructure | Wood | Track rail masts |
| | Plastic | Canalizations/sewage |

economic to psychological aspects, including social and cultural backgrounds. A list of some services and examples from carbon-based materials are shown in table 2.

From a modeling perspective, consumption patterns in material systems rely on a service-oriented per capita consumption, population dynamics and expected in-use lifetime of goods

(Kishino et al., 1999; UNEP, 2010). The annual service-oriented per capita consumption of goods is estimated with equation (8) considering saturation consumption patterns and the dynamics for reaching this point. Non-exponential behaviors are assumed for the consumption of goods; but rather a natural trend to level-off the demand after the service for the whole population starts to be fulfilled. In this sense, a logistic approach is taken to estimate the annual per capita consumption.

$$\boldsymbol{CpC_t^{mg,ser} = CpC_{t0}^{mg,ser} + \left( \frac{CpC_{tf}^{mg,ser} - CpC_{t0}^{mg,ser}}{1 + e^{-\left(\frac{t-t_\Delta}{\tau}\right)}} \right)} \tag{8}$$

$\boldsymbol{with}$,

$\boldsymbol{CpC_t^{mg,ser}}$ = $\boldsymbol{Per\ capita\ consumption\ per\ service\ and\ material\ at\ period\ t\ (kg/cap)}$

$\boldsymbol{CpC_{t0}^{mg,ser}}$ = $\boldsymbol{Per\ capita\ consumption\ per\ service\ and\ material\ at\ initial\ period\ (kg/cap)}$

$\boldsymbol{CpC_{tf}^{mg,ser}}$ = $\boldsymbol{Per\ capita\ consumption\ per\ service\ and\ material\ at\ final\ period\ (kg/cap)}$

$\boldsymbol{t_\Delta}$ = $\boldsymbol{Inflexion\ year\ (yr)}$

$\boldsymbol{\tau}$ = $\boldsymbol{Transition\ year\ coefficient\ (yr)}$

In combination with the population dynamics and the annual internal market share, the domestic per capita consumption is used to estimate the annual domestic demand per product-service unit with equation (9). This heuristic value of the domestic demand is used for the calculation of raw material demands (primary and secondary) and to estimate annual production considering foreign trade, as explained in detail in section 3.3.1. The solution to the final domestic demand is found with equation (10), with information from the manufacturing sector. As seen, both equations estimate a value for the domestic demand converging in the solution of the required volumes of raw materials.

$$\boldsymbol{D_{j,t}^C = MS_{j,t}^{mg} \times Pop_t \times CpC_t^{mg,ser}} \tag{9}$$

$\boldsymbol{with}$,

$\boldsymbol{D_{j,t}^C}$ = $\boldsymbol{Domestic\ demand\ per\ product\ group\ from\ per\ capita\ consumption\ (kg/a)}$

$\boldsymbol{MS_{j,t}^{mg}}$ = $\boldsymbol{Market\ share\ per\ material\ and\ product\ group}$ (%)

$\boldsymbol{Pop_t}$ = $\boldsymbol{Population\ at\ period\ t\ (Mio.)}$

$\boldsymbol{CpC_t^{mg,ser}}$ = $\boldsymbol{Per\ capita\ consumption\ for\ service\ and\ product\ group\ at\ period\ t\ (kg/cap)}$

$$\boldsymbol{D_{j,t}^H = X_{j,t}^H + X_{j,t}^{imp} - X_{j,t}^{exp}} \tag{10}$$

$\boldsymbol{with}$,

$\boldsymbol{D_{j,t}^H}$ = $\boldsymbol{Domestic\ demand\ per\ product\ group\ j\ estimated\ with\ production\ coefficients\ (kt/a)}$

$\boldsymbol{X_{j,t}^H}$ = $\boldsymbol{Domestic\ production\ per\ material\ and\ product\ group}$ (%)

$\boldsymbol{X_{j,t}^{imp}}$ = $\boldsymbol{Imported\ goods\ per\ product\ group\ (kt/a)}$

$\boldsymbol{X_{j,t}^{exp}}$ = $\boldsymbol{Exported\ goods\ per\ product\ group\ (kt/a)}$

### In-use lifetime of consumer and capital goods

The second important variable to model the consumption sector is the in-use life of products. It is a central feature and provides essential information for the whole dynamic EW-SFM modeling. In dynamic stock-flow models the life cycle of a product influences raw material requirements, consumption patterns, availability of secondary raw materials and stock dynamics. The terminology "lifetime" may have several meanings depending on the defined scope of analysis. Lifetime can be defined as: (1) the time between the product is in-use from the first possession by a consumer and its discard to waste treatment processes, (2) the time between its production and a final owner, (3) the time as the product was still in separated component (production of parts) and the recycling of this parts after use to new products, and many other combinations. Oguchi et al. (2010) examines different approaches to estimated products' lifetime and comes to the conclusion that any of the methodologies for estimation of lifetime distributions are applicable considering, however, the representativeness of the data. In other words, it is the scope and objective of a study what determines how the term is defined. It is also argued that the shipment time should be included in the "lifetime" of the product; however information about the shipment's year is difficult to estimate when no tracking systems are incorporated. Thus, the in-use lifetime of finished goods is defined by a "discard-based distribution" (Oguchi et al., 2010) that provides the most accurate approach for analyzing use and discard of commodities in a material system and corresponds to the first definition.

These product life cycle distributions are estimated with several probability density functions, like Weibull, gamma, exponential, normal, log-normal distributions, Cauchy, among others. In the literature a number of studies have achieved very good approximations for stock-flow modeling with Weibull distributions at regional (Walk, 2009) and national level (Daigo et al., 2009) with Gamma distributions (Marland et al., 2009) as well, both after a proper estimation of curve parameters. Also the Normal distribution has been used (Müller, 2006; Hu et al., 2010a), when information about the life cycle distributions is lacking, as this function requires only the mean and standard deviation values. Other studies have considered the exponential function (Marland and Marland, 2003; Elshkaki et al., 2005), widely used to simulate natural decay happening in forests and dead matter. For carbon-based materials in AMS natural decay is not present in large extent due to consumption patterns, material stability during the in-use phase and the absence of leaching processes. Here, oxidation mechanisms occur very quick mainly under combustion processes conditioned by the consumer behavior in the extension or shortening of the product in-use lifespan. Finally, because of the wide product palette availability, in-use lifetimes must be further classified according to the expected time of use. Consumer goods have a tendency of having shorter in-use lifetimes, compared to capital goods (built environments and infrastructure). Therefore, some products are promptly used while others stay for decades before being discarded. The discard behavior of these types of goods cannot be unified. A four-level classification will be used as discussed in section 3.3.3.

A wide modeling options for the in-use lifetime of products are possible which influences, with additional criteria such as observed behavior, type of product and available information, the selection of the probability density function (PDF). Even more, due to the high variability of the materials and goods, in-use patterns of finished products are expressed in in-use lifetime ranges of minimum, maximum and expected years. Considering similar in-use lifespans for all product groups might bring misleading results. Thus, the in-use lifetime product distributions go from less than one year to several decades. Because of the wide variety of products, a lifetime product classification is necessary to enable flexibility in the turnover rate and stock formation.

$$\boldsymbol{t^{ig,d}} = \sum_{j=1}^{m} \boldsymbol{a_j t_{j,d}^{ig}} \ \forall \ \boldsymbol{ig} \tag{11}$$

***with***,
$\boldsymbol{t^{ig,d}}$ = ***Discard time per in − use lifetime group*** $(\boldsymbol{a})$
$\boldsymbol{a_j}$ = ***Product weighting fraction within market share*** (%)
$\boldsymbol{t_{j,d}^{ig}}$ = ***Discard time of product j per in − use lifetime group ig*** $(\boldsymbol{a})$
$\boldsymbol{d}$ = ***Minimum, maximum or expected discard time of product j*** $(\boldsymbol{a})$

The product classification includes short, middle, long and very long in-use lifetimes to permit a wide variation of turnover rates in products. Using equation (11) the minimum, maximum and expected discard times of these lifetime groups is computed. Because of the time dependent probability of occurrence from the discarded post-consumer wastes, it is required the use of a very flexible and adaptable probability distribution. A proper option for modeling of material systems in the anthroposphere is the Weibull distribution, shown in equation (12), for its simplicity and adaptability to different discard patterns, as well as the capability of modeling times of occurrence of events where the probability of occurrence changes with time. In other words, the distribution has "memory", as opposed to other probability distributions where the probability of occurrence remains constant, or "memoryless". Additionally, the flexibility of the Weibull distribution enables the representation of other common probability distributions. For example, it becomes an exponential distribution when its parameter $\alpha_t^{ig}$= 1 or practically a normal distribution when $\alpha_t^{ig}$= 3.25. This flexibility allows a better representation of the discarding pattern of the post-consumer waste, where the parameters $\alpha_t^{ig}$and $\beta_t^{ig}$ are defined for each in-use lifetime group annually. The former parameter controls the shape of the distribution, skewness or kurtosis, while the latter the spread of the distribution.

$$\boldsymbol{f\left(t, t_0^{ig}, \alpha_t^{ig}, \beta_t^{ig}\right)} = \begin{Bmatrix} \boldsymbol{\alpha_t^{ig} \beta^{-\alpha_t} \left(t - t_0^{ig}\right)^{\alpha_t^{ig}-1} e^{-\left(\frac{t-t_0^{ig}}{\beta_t^{ig}}\right)^{\alpha_t^{ig}}}} & \textbf{if } \boldsymbol{t > t_0^{ig}} \\ \boldsymbol{0} & \textbf{Otherwise} \end{Bmatrix} \tag{12}$$

***with***,
$\boldsymbol{f\left(t, t_0^{ig}, \alpha_t^{ig}, \beta_t^{ig}\right)}$
= ***Probabilistic rate of discard per period and in − use lifetime group***
$\boldsymbol{t}$ = ***Period t*** $(\boldsymbol{a})$
$\boldsymbol{t_0^{ig}}$ = ***Minimum discard time per in − use lifetime group*** $(\boldsymbol{a})$
$\boldsymbol{\alpha_t^{ig}}$ = ***Scale parameter in probability function***
$\boldsymbol{\beta_t^{ig}}$ = ***Shape parameter in probability function***

Following a normal distribution model within a 3σ-range, in equation (13) it is assumed that the discarded amount of post-consumer corresponds to 99.7% of the total amount of consumed input. These parameters are found by solving equations (13) and (14), and are afterwards replaced in equation (12) to determine the rate of discard of each in-use lifetime group per year.

$$\mathbf{99.7\% = p\left(t_0^{ig} \le t_{mean}^{ig} \le t_f^{ig}\right) = 1 - e^{-\left(\frac{t_f^{ig} - t_o^{ig}}{\beta_t^{ig}}\right)^{\alpha_t^{ig}}}} \quad (13)$$

$\mathbf{with,}$

$\mathbf{t_0^{ig}}$ = $\mathbf{Minimum\ discard\ time\ per\ in-use\ lifetime\ group\ (a)}$

$\mathbf{t_f^{ig}}$ = $\mathbf{Maximum\ discard\ time\ per\ in-use\ lifetime\ group\ (a)}$

$\mathbf{t_{mean}^{ig}}$ = $\mathbf{Mean\ discard\ time\ per\ in-use\ lifetime\ group\ (a)}$

$\boldsymbol{\alpha_t^{ig}}$ = $\mathbf{Scale\ parameter\ in\ probability\ function}$

$\boldsymbol{\beta_t^{ig}}$ = $\mathbf{Shape\ parameter\ in\ probability\ function}$

$$\mathbf{t_{mean}^{ig} = t_0^{ig} + \boldsymbol{\beta}_t^{ig}\left(\frac{\boldsymbol{\alpha}_t^{ig} - 1}{\boldsymbol{\alpha}_t^{ig}}\right)^{1/\boldsymbol{\alpha}_t^{ig}}} \quad (14)$$

$\mathbf{with,}$

$\mathbf{t_0^{ig}}$ = $\mathbf{Minimum\ discard\ time\ per\ in-use\ lifetime\ group\ (a)}$

$\mathbf{t_{mean}^{ig}}$ = $\mathbf{Mean\ discard\ time\ per\ in-use\ lifetime\ group\ (a)}$

$\boldsymbol{\alpha_t^{ig}}$ = $\mathbf{Scale\ parameter\ in\ probability\ function}$

$\boldsymbol{\beta_t^{ig}}$ = $\mathbf{Shape\ parameter\ in\ probability\ function}$

The in-use lifetime of products is modeled under a probabilistic approach. Figure 9 shows the expected behavior of each in-use lifespan group of the carbon-based materials using the Weibull distribution.

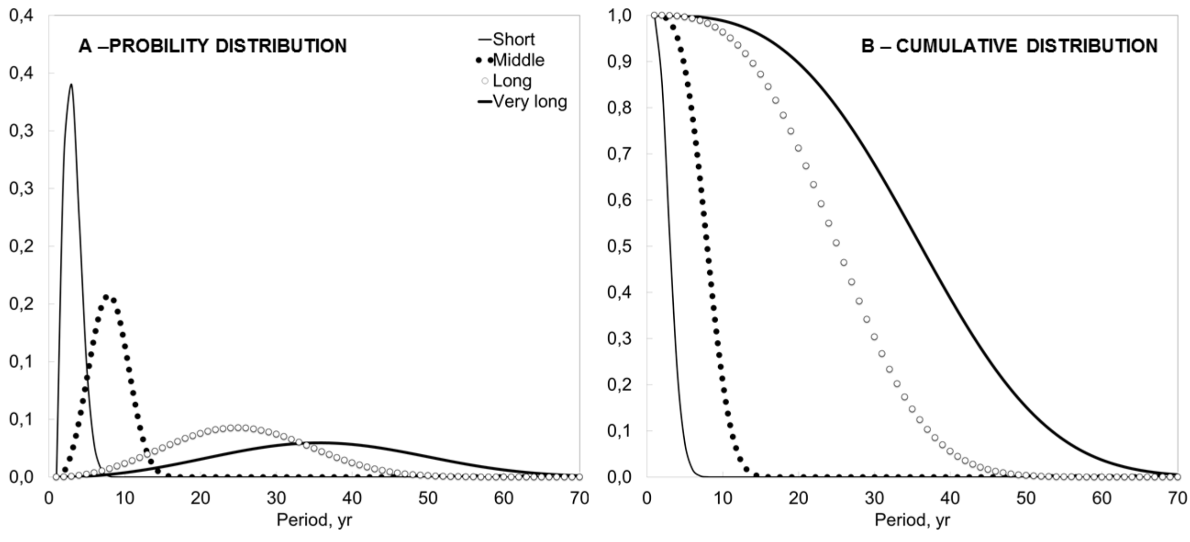


Figure 9: Probabilistic approach to modeled discard of carbon-based products using Weibull distribution

## Consumption behavioral patterns: reuse or refuse of goods

The third important aspect to recall in the consumption sector is the behavioral consumption patterns, which also affects the manufacturing volumes. Behavioral patterns are strongly related with the time a product is consumed. Changes in consumption patterns are inherent characteristics of AMS, as it is mainly driven by human action. It is thus, important to include such variability and option within the stock-flow modeling.

Consumption patterns are expressed in both the reuse and refuse of products; that is, the avoidance or acceleration of discarding products into post-consumer waste outflows expressed as the shortening or lengthening of the product in-use lifetime, respectively. Mathematically speaking, the variation of the in-use lifetime of goods is a probabilistic change based on the used probability density function (Weibull) and the product lifetime information. When the product lifespan varies after a voluntarily (or legally bound) human decision, either longer or shorter maximum and expected in-use lifetimes change proportionally with respect to a reference values. The reference value is obtained with distribution of the initial in-use lifetime data for each product group. Behavioral patterns are then represented with the differences between a probability reference in-use value and an altered one along the whole simulation time period. Reuse or refuse of goods is modeled and estimated with equation (15) as the probabilistic difference of a reference discard rate and an alternate rate caused by the changes in consumption behavior patterns. In other words, the change of the expected discard time of a product is the mathematical expression of the reuse (or refuse) patterns.

$$\boldsymbol{WD_t^{ig}} = \boldsymbol{\phi_{t=t0}^{ig} - \phi_{t\neq t0}^{ig}} \tag{15}$$

$\boldsymbol{with,}$

$\boldsymbol{WD_t^{ig}}$ = $\boldsymbol{Probabilistic\ change\ in\ expected\ discard\ in\ post - consumer\ waste\ volumes\ (t)}$

$\boldsymbol{\phi_t^{ig}}$ = $\boldsymbol{Probabilistic\ discard\ value\ from\ probability\ density\ function\ \Phi(ig, y)}$

$\boldsymbol{t = t_0}$ = $\boldsymbol{\phi\ value\ at\ reference\ in - use\ lifespan}$

$\boldsymbol{t \neq t_0}$ = $\boldsymbol{\phi\ value\ at\ evaluated\ in - use\ lifespan}$

The total volume of reused or refused goods influenced by behavioral consuming patterns is calculated with equation (16).

$$\boldsymbol{X_{j,t}^{ru}} = \sum_{\boldsymbol{t}} \boldsymbol{WD_t^{ig} \times W_{j,t}^{ig}} \tag{16}$$

$\boldsymbol{with,}$

$\boldsymbol{X_{j,t}^{ru}}$ = $\boldsymbol{Reused\ or\ refused\ goods\ of\ product\ group\ j\ (kt/a)}$

$\boldsymbol{WD_t^{ig}}$ = $\boldsymbol{Probabilistic\ change\ in\ expected\ discard\ in\ post - consumer\ waste\ volumes\ (t)}$

$\boldsymbol{W_{j,t}^{ig}}$ = $\boldsymbol{Post - consumer\ waste\ per\ in - use\ lifetime\ group\ and\ product\ group\ (kt/a)}$

This change has subsequent effects in the manufacturing requirements of products along the periods, which implies a variation in the raw material demand, either in the reduction for new raw materials caused by the surplus of in-use products or a need of more resources to satisfy the missing manufacturing demand at each time period. The reuse and refuse in consumption patterns, focuses on consumer goods. Capital goods do not have such strong effects as their influence and use goes beyond one single personal motivation and choice.

**Stocks in the anthroposphere**

In chapter 1 material flows and stocks in the anthroposphere were introduced as a fundamental concept for the development and subsistence of material systems and societal metabolism. The current discussed EW-SFM estimates anthropogenic mass flows and stocks within a system boundary, based on annual time frames. Stock dynamics (annual change and cumulative building) are determined for each in-use lifetime group as the difference between the total consumed products and the corresponding group post-consumer waste outflow of the same period as described in equation (17). The dynamics of stocks are calculated starting with an initial stock value estimated under regression analysis based on statistical time series. Stock dynamics in the anthroposphere are driven by the consumption of goods and influenced by variations in product demands, behavioral and reuse patterns and in-use lifetime of goods.

$$\boldsymbol{S_t^{ig} = D_t^{ig} - W_t^{ig} + S_0 \; \forall \; ig} \tag{17}$$

$\boldsymbol{with,}$

$\boldsymbol{S_t^{ig}} \quad = \boldsymbol{Stocks\ in\ period\ t\ per\ in-use\ lifetime\ group\ (kt)}$

$\boldsymbol{D_t^{ig}} \quad = \boldsymbol{Domestic\ demand\ per\ in-use\ lifetime\ group\ (kt/a)}$

$\boldsymbol{W_t^{ig}} \quad = \boldsymbol{Domestic\ waste\ per\ in-use\ lifetime\ group\ (kt/a)}$

$\boldsymbol{S_0} \quad = \boldsymbol{Initial\ stocks\ value\ in\ period\ t_0}$

The model historic values of stocks are estimated as the sum of annual change of stocks per product group until present time. This value is needed as this will become part of the waste outflow in the future. The periods to estimate the built stock depend on the average in-use lifetime of the good, which mostly affects long lifetime goods. The estimation of current and future stocks is a combination of a retrospective and a prospective analysis modeled along the evaluated periods. The absence of stocks in some sectors derives of the short residence time of materials, that is, less than one year. It is assumed that stocks are mostly present in the consumption sector and in the biogenic system, while in the manufacturing, market and waste management sector no formation is expected.

### 3.3.4. Solid waste management sector

The solid waste management sector procures resource-rational and environmental-oriented management of post-industrial and post-consumer wastes for the construction and deployment of the circularity paradigm. It is one main pillar for the construction of a sustainable development. The solid waste management sector handles post-industrial and post-consumer waste, from domestic or foreign origin. This waste is recovered and allocated in terms of volumes with different sorting technologies in the available waste treatment processes. Despite the multiple technologies for waste treatment processes, the three most currently propagated methods are incineration (or combustion) of wastes used for both energy and non-energy purposes, landfilling and recycling. Other waste treatment processes are composting and gasification which are mainly used for treatment of biodegradable household waste (Knappe and Dehoust, 2007). Because of the carbon-based volumes they are not considered in detail in the modeling process.

In figure 3 the waste management sector and the combustion sector appear as two separate sectors. This is done to indicate the partial belonging of the latter to the waste treatment processes. The division enables the modeling of carbon emissions from both wastes and final goods used for energy purposes separately but in one single sector. The incineration of waste, the decomposition of wastes in landfills and the use of energy carries for domestic services all takes place in this ’satellite’ sector. The solid waste management sector (without the combustion sector) is illustrated in figure 10 and described by equation (A.5) in Annex A, where post-industrial and post-consumer wastes outflows plus material flows for energy uses are distributed into different waste treatment processes.

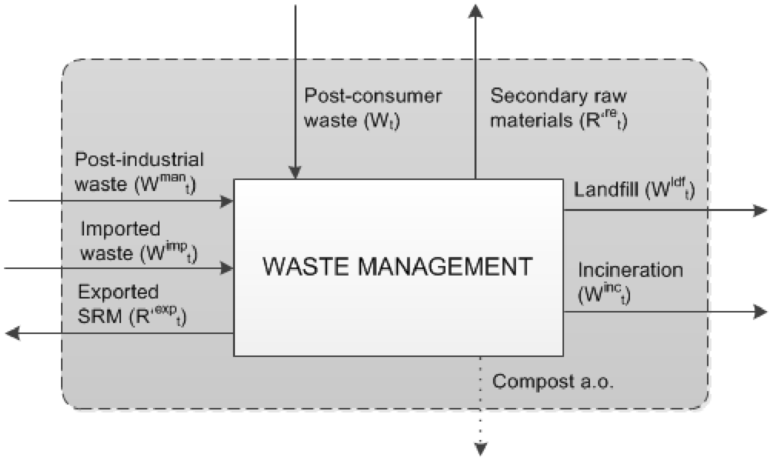


Figure 10: Detailed waste management sector flows and system boundary

The per in-use lifetime waste volumes are subsequently distributed and allocated under different waste treatment processes for material and energy purposes. As said, the set of main available technologies for waste treatment are recycling, landfilling and incineration, with additional but minor processes like gasification, composting which are not consider in the model. Landfilling which is discussed in detail in section 3.3.5., is still a widely used technology worldwide, though in Europe it has been reduced or it is highly restricted. The distributions fractions of each waste treatment process are estimated based on policies goals and statistical data, which vary on time correspondingly to the development share of each waste treatment processes. Thus, the sector takes into account the development, changes or improvements of recycling, incineration and landfill technologies and shares among time. The incorporation of exported secondary raw material is also considered. Additionally, a fraction of the final recycled material flow is exported as secondary raw materials.

A worrying aspect of the post-consumer waste management lies unfortunately outside the range of action of the waste management sector. The waste management sector has flaws at recovery and distribution phases where material losses lead to undesirable littering. Even more, this problem is intensified with irresponsible consumer behavior. One of the major littering problems nowadays encountered in almost every coastal area is marine littering of plastics which causes great damage in aquatic species and marine ecosystems (Schulz et al., 2015). Because the difficulty to track such flows in the ecosystems for the modeling purposes it was omitted. Nevertheless, despite the best performance of the waste treatment technologies, a lack of environmental consciousness will bring nothing to the technological advance.

## Post-industrial and post-consumer waste flows

The main inflows to the waste management sector are the post-industrial and post-consumer waste flows. The post-industrial flow is composed of by-products of the manufacturing sector and compiles both raw materials and residues of semi-finished products. In most cases, post-industrial flows are materially used (mechanical recycling) with a smaller portion in energy applications. Post-industrial flows are estimated in basis of manufacturing efficiencies and are either recycled or incinerated. On the other side, post-consumer wastes are determined using product information, that is, the in-use lifetime and a probability distribution, as discussed in section 3.3.3. The annual post-consumer waste per lifetime group is defined with equation (18) used to estimate the total waste outflow per period as the sum of all in-use lifetime groups.

$$\boldsymbol{W_t^{ig}} = \sum_{y=0}^{t} \boldsymbol{D_{j,t-y}} \int_{y}^{y+1} \boldsymbol{\Phi_y^{ig}}\, dy \qquad (18)$$

$with,$
$W_t^{ig}$ = $Post - consumer\ waste\ per\ in - use\ lifetime\ group\ (kt/a)$
$D_{j,t-y}$ = $Domestic\ consumption\ of\ product\ group\ j\ at\ period\ t - y\ (kt/a)$
$\Phi_y^{ig}$ = $Probability\ density\ function\ of\ the\ in - use\ lifetime\ groups\ as\ discard\ period$
$y$ = $Year\ of\ discard\ (a)$

Because of the material heterogeneity within each in-use lifetime waste outflow, it is necessary a precise classification and quantification in terms of both materials and in-use lifetime groups. Equation (19) provides a thorough volume discrimination of each material group for potential material use within the non-combustion waste treatment process. Therefore, waste volumes are then allocated in each waste treatment process accordingly to each in-use lifetime groups and material group. The distribution fractions of the post-consumer wastes for each waste treatment process and material group are estimated at the retrospective modeling with time-series data, while in the prospective assumptions of the expected waste treatment development shares are given.

$$\boldsymbol{W_t^{ig,\omega}} = \boldsymbol{\rho_t^{ig,\omega}} \sum \boldsymbol{W_t^{mg,ig}}\ \forall\, \boldsymbol{mg} \qquad (19)$$

$with,$
$W_t^{ig,\omega}$ = $Post - consumer\ waste\ per\ treatment, in - use\ lifetime\ and\ material\ group\ (kt/a)$
$\rho_t^{ig,\omega}$ = $Distribution\ factor\ for\ waste\ treatment\ \omega$ (%)
$W_t^{mg,ig}$ = $Post - consumer\ waste\ per\ material\ and\ in - use\ lifetime\ group\ (kt/a)$

Finally, post-consumer waste volumes for each treatment process per in-use lifetime and material group are expressed in volumes of final goods as the partial sum of wastes per period. This provides a more concrete insight of the waste volumes, composition, distribution and proper estimation of incineration emissions. Using equation (20) post-consumer wastes per product group are estimated for each waste treatment processes based on the annual consumption share.

$$W_{j,t}^{\omega} = \sum_{t=0}^{y}\left(W_t^{ig,\omega} \times \frac{D_{j,t}^{mg,ig}}{\sum_{j=1}^{m} D_{j,t}^{mg,ig}}\right) \forall\, ig, \forall\, mg \tag{20}$$

$with,$
$W_t^{\omega}$ = $Post - consumer\ waste\ per\ product\ group\ to\ waste\ treatment\ (kt/a)$
$W_t^{ig,\omega}$ = $Post - consumer\ waste\ for\ treatment\ per\ in - use\ lifetime\ and\ material\ group\ (kt/a)$
$D_{j,t}^{mg,ig}$ = $Domestic\ demand\ per\ material\ and\ in - use\ lifetime\ group\ (kt/a)$
$y$ = $Year\ of\ discard\ (a)$

## Recycling and secondary raw materials

From a material perspective, recycling of post-industrial and post-consumer waste is a fundamental step in the development of the circularity paradigm as it provides volumes of secondary raw materials to be used in manufacturing processes reducing resource demand pressure of primary raw materials. Recycled wastes provide a detailed quantification of potential efficient use for each secondary raw material in perspective of downcycling and substitution potentials. The recycled post-consumer waste requires a clear distinction in terms of classification and raw material composition, as the recovered waste has varying quality and recyclable characteristics. Further, post-consumer wastes are expressed in final goods and the recycled volumes in terms of raw materials. Therefore, the composition and supply of secondary raw materials destined to the manufacturing sector are calculated with equation (21) using the information of the production function matrix (see table A.9 in Annex A). This result illustrates the potential volumes of recycled raw materials.

$$R'^{re}_{i,t} = \sum_{j=1}^{n} h_{i,j} \times W_{j,t}^{re}\ \forall\, i \tag{21}$$

$with,$
$R'^{re}_{i,t}$ = $Potential\ recycled\ raw\ materials\ i\ (kt/a)$
$h_{i,j}$ = $Production\ function\ coefficient$
$W_{j,t}^{re}$ = $Post - consumer\ waste\ for\ recycling\ per\ product\ group\ (kt/a)$
$n$ = $Number\ of\ processed\ raw\ materials$

Because of the recovery mechanisms, post-consumer waste for recycling contains unwanted material varying from one material group to the other. Thus, the modeling of the recycling flow is firstly characterized assuming a pre-treatment (or depollution) process to select net recyclable from non-recyclable material. It is assumed that a thorough separation of additives and hazardous components takes place, which are incorporated in the incineration material.

On the other hand, foreign trade of secondary raw materials is an important economic activity. Thus, a fraction of secondary raw materials flows from the anthropogenic system out into the foreign trade system. The resting amount is used in the manufacturing sector and it is estimated with equation (22). Finally, equation (23) provides the volumes form recycling process that are thermally used, which are discussed in detail in the section below.

$$\boldsymbol{R'^{man}_t = \eta^{re}_{mg} \times R'^{re}_{i,t} \times \left(1 - \rho^{ig,exp}_t\right) \forall\, i} \tag{22}$$

$\boldsymbol{with},$

$\boldsymbol{R'^{man}_t}$ = $\boldsymbol{Recycled\ raw\ materials\ to\ manufacturing\ sector\ (kt/a)}$

$\boldsymbol{\eta^{re}_{mg}}$ = $\boldsymbol{Recycling\ depollution\ factor\ per\ material\ group}$ (%)

$\boldsymbol{R'^{re}_{i,t}}$ = $\boldsymbol{Potential\ recycled\ raw\ materials\ i\ (kt/a)}$

$\boldsymbol{\rho^{ig,exp}_t}$ = $\boldsymbol{Distribution\ factor\ for\ recycled\ material\ exports}$ (%)

$$\boldsymbol{R'^{inc}_t = \left(R'^{re}_{i,t} + W^{man,\omega}_{i,t}\right) \times \left(1 - \eta^{re}_{mg}\right) \forall\, i} \tag{23}$$

$\boldsymbol{with},$

$\boldsymbol{R'^{inc}_t}$ = $\boldsymbol{Non-suitable\ recycled\ raw\ materials\ to\ incineration\ (kt/a)}$

$\boldsymbol{R'^{re}_{i,t}}$ = $\boldsymbol{Potential\ recycled\ raw\ materials\ i\ (kt/a)}$

$\boldsymbol{W^{man,\omega}_{i,t}}$ = $\boldsymbol{Post-industrial\ raw\ material\ waste\ to\ waste\ treatment\ processes\ (kt/a)}$

$\boldsymbol{\eta^{re}_{mg}}$ = $\boldsymbol{Recycling\ depollution\ factor\ per\ material\ group}$ (%)

$\boldsymbol{\omega}$ = $\boldsymbol{Waste\ treatment\ process\ (incineration)}$

### 3.3.5. Combustion, landfilling and carbon emissions

Thermal oxidative processes for waste treatment are a widely deployed technology that used the thermal capacity of the materials and decomposes chemically most of hazardous substances into less risky compounds. The incineration processes are normally taken place in equipment such as grate furnace or fluidized bed firing vessel (Klein and Kubisa, 1994; Lahl and Steven, 2009; Richers, 2010). Both post-consumer and post-industrial waste flows are incinerated for energy and non-energy uses. Along with the decomposition of waste flows, the use of final goods for energy purposes like transportation or domestic heating (expressed as $F_t$ in equation (24)) are also included in this subsector as both are part of the anthropogenic activities, its combustion technology are similar and contribute to the carbon-related emissions. Despite these two separate uses, the emissions estimation have equal relevance on both purposes, that is, energy recovery from wastes and final goods or thermal decomposition of normally hazardous wastes or non-recyclable waste. Further, the emissions coming from landfills are also considered. Figure 11 illustrates the flows and emissions considered in the model.

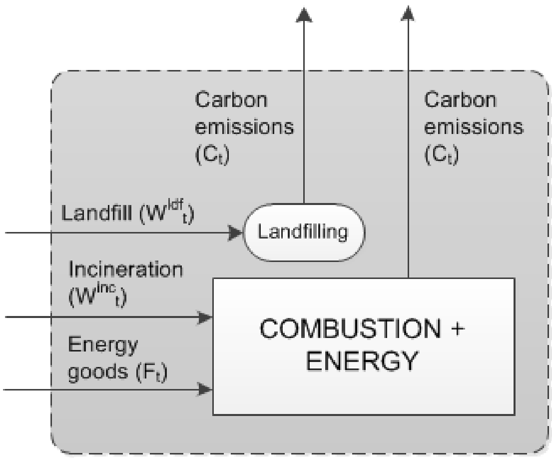


Figure 11: Detailed combustion and carbon emissions sector flows and system boundary

The modeling and carbon emissions calculation of the three mentioned material flows (landfill, incineration and energy goods) are estimated in this sector. The emissions volumes from elementary carbon content of final goods for energy use, post-consumer, post-industrial, landfilling and recycling waste flows in the different sectors in the AMS are taken into consideration, for the estimation of total carbon-related emissions in the AMS.

## Combustion

From equations (5), (20) and (23) we obtain the annual incineration volumes from each product group waste and raw material residues. Further, the annual consumption volume of the short in-use lifetime products for energy purposes is added directly to the combustion volumes for energy uses. The model assumes no stock building from these final goods and the residues of incineration, like ashes or slack, that are disposed correspondingly to current regulations (landfilled). Nevertheless, because of the carbon-oriented flows and emissions modeling, the volumes of slack and ashes are not quantified. The volume of carbon emissions is estimated with elementary contents of carbon from elementary average composition of each raw material and material groups for incineration flows, and calculated with equations (24) and (25), respectively.

$$C_{i,t} = \sum_{i=1}^{m} R'^{inc}_{t} \times c_{i,t} \tag{24}$$

$with,$
$C_{i,t}$ = $Carbon\ content\ in\ raw\ materials\ for\ combustion\ processes$ $(kt/a)$
$R'^{inc}_{t}$ = $Non-suitable\ recycled\ raw\ materials\ to\ incineration$ $(kt/a))$
$c_{i,t}$ = $Elementary\ carbon\ concentration\ in\ raw\ materials$ (%)
$m$ = $Number\ of\ product\ groups$

$$C_{j,t} = \sum_{j=1}^{n} \left(W^{\omega}_{j,t} + F_t\right) \times c_{j,t} \tag{25}$$

$with,$
$C_{j,t}$ = $Carbon\ content\ in\ material\ groups\ for\ combustion\ processes$ $(kt/a)$
$W^{\omega}_{j,t}$ = $Post-consumer\ waste\ per\ product\ group\ to\ waste\ treatment\ process$ $(kt/a)$
$F_t$ = $Domestic\ energy\ goods$ $(kt/a)$
$c_{j,t}$ = $Elementary\ carbon\ concentration\ in\ material\ groups$ (%)
$n$ = $Number\ of\ processed\ raw\ materials$

Total carbon emissions are expressed in carbon dioxide equivalent ($CO_2$-eq) and are calculated with equation (26) based on the reference global warming potential (GWP100) and technology combustion parameters. The same equation is used for the other combustion gases such as nitrous oxide ($N_2O$) using values of elementary nitrogen. However, because of the very low concentration of these gases total carbon emissions only takes into consideration the values of elementary carbon. In table A.5 in Annex A incineration data for the estimation of carbon emissions is found. Carbon-based materials are a mixture of elements, mostly composed of carbon between 43% and 83% C w/w (Lemann, 2008; Young, 2010). Table A.6 also in Annex A provides the average composition of the material groups.

$$\dot{C}_t = \sum \left(C_{i,t} + C_{j,t}\right) \times V^g \times GWP_{100} \times \xi \tag{26}$$

$with,$
$\dot{C}_t$ = $Carbon\ emissions\ in\ CO_2 - eq$ $(kt/a)$
$C_{i,t}$ = $Carbon\ content\ in\ raw\ materials\ for\ combustion\ processes$ $(kt/a)$
$C_{j,t}$ = $Carbon\ content\ in\ material\ groups\ for\ combustion\ processes$ $(kt/a)$
$V^g$ = $Combustion\ gas\ composition$ (%)
$GWP_{100}$ = $Global\ warming\ potential\ value$
$\xi$ = $Stoichiometric\ combustion\ ratio$

## Landfilling

The decay of biodegradable organic material of the post-consumer and post-industrial waste outflows become significant sources of carbon emission from landfills. Stronger policies have been put into practice to restrict landfilling activities, for instance in 2005 it was banned in Germany and only treated wastes like ashes, slags and burnt residues are landfilled. Nevertheless, its current stocks have still emissions potential for coming years in the form of methane ($CH_4$) and carbon dioxide ($CO_2$). Therefore, the modeling of emissions from landfills assumes an exponential decay (Micales and Skog, 1997) behavior of matter for each material group. Landfill emissions from non-treated post-consumer waste are present, as this was a main waste treatment process in the past decades. Using equation (27) the amount of potential gas emission from landfills from accumulated waste is estimated.

$$L_t^{CH4} = \sum_{y=0}^{y} W_t^{ig,\omega} \times v^{mg} \times e^{-ky} \tag{27}$$

$$\begin{aligned}
&\textbf{with,}\\
&L_t^{CH4} &&= \textit{Methane emissions from landfill activities } (kt/a)\\
&W_t^{ig,\omega} &&= \textit{Post-consumer waste for waste treatment per in-use lifetime and material group } (kt/a)\\
&v^{mg} &&= \textit{Methane generation potential per material group } (tCH4/tWaste)\\
&k &&= \textit{Methane generation rate } (1/a)\\
&y &&= \textit{Year of discard } (yr)
\end{aligned}$$

The generation of $CH_4$ is complemented with the generation other minor gases and of $CO_2$, which also contributes to the total annual carbon emissions. With equation (28) the corresponding amount of carbon dioxide emitted from landfill activities is estimated, where the methane fraction of landfill gas is assumed to be $k' = 0.5$ and the soil oxidation factor of $k'' = 0.1$ (Cruz and Barlaz, 2010; RTI, 2010).

Similarly to the estimation of $CO_2$-eq at the combustion sector, the volumes of gas from landfills are also expressed in this term. Finally, before the 2005 landfill ban in Germany, carbon-based materials cause GHG emissions, mostly by anaerobic decomposition. These emissions correspond to paper and wood residues, as the decay rate of plastics wastes is very low and it is assumed to be zero. After this year landfilling and incineration are merged into the same category; thus, current landfilling processes manage incineration residues and ashes.

$$L_t^{CO2} = L_t^{CH4} \times \left(\frac{1-k'}{k'} + k''\right) \times \frac{\overline{CO_2}}{\overline{CH_4}} \tag{28}$$

$$\begin{aligned}
&\textbf{with,}\\
&L_t^{CO2} &&= \textit{Carbon emissions from landfill activities } (kt/a)\\
&L_t^{CH4} &&= \textit{Methane emissions from landfill activities } (kt/a)\\
&k' &&= \textit{Methane fraction in landfill gas}\\
&k'' &&= \textit{Soil oxidation factor}\\
&\overline{CO_2} &&= \textit{Molecular weight of carbon dioxide } (g/mol)\\
&\overline{CH_4} &&= \textit{Molecular weight of methane } (g/mol)
\end{aligned}$$

In this section the mathematical framework of the model to describe a material system in the anthroposphere has been discussed. As explained in detail above, the balancing of raw materials volumes for manufacturing processes found both outside and inside the anthropogenic system with the volume required to satisfy consumption demands considering foreign trade in annual time slots is estimated. Raw materials flow into the anthropogenic system as processed raw materials (or semi-finished goods) for production of final goods. With determined product in-use lifetimes, final goods forge dynamic stock building and generation of post-consumer wastes along time. In-use lifetime of final products in the consumption sector are modeled with probability density functions to quantify periodically rates and amount in outflows to the waste treatment processes and subsequently the effects in stock dynamics. Products and goods at its end-of-life become post-consumer wastes, and are treated under various processes for recovery of raw materials for material and energy uses.

### 3.4. Trade-offs and reliability of the dynamic model

Modeling reality is limited by the knowledge, the understanding of its complexity, the resilience and feedbacks of the modeled system. Also the availability of necessary information and data is normally incomplete and with a component of uncertainty. Thus, modeling systems become a representation, as adequate as possible, of the real world from a set of continuous or discrete variables normally under a mathematical system framework. Having fully described the structure of the dynamic model a significant three-step modeling procedure is performed (Jorgensen and Bendoricchio, 2001) to provide a plausible ground for the model results. First a verification of the model is made, followed by a calibration and finalizing with a validation of output data. This procedure provides reliability in the results and logical behavior of the system to predict past and future stages.

#### 3.4.1. Verification

The model has been constructed under mass basis units. Flows are calculated in kilotons per year (kt/a) or million tons per year (Mt/a) and stocks in kilotons (kt) or million tons (Mt). Some other parameters have either different dimensional units or are dimensionless, but have an influence in the final mass balance of the model. With a mass balance evaluation of the sectors and the complete AMS, the consistency, stability and internal systemic structure of the model are verified. This latter indicates logical and satisfactory reactions that the model should display, for example an increase in the consumption of goods should be reflected in a larger volume of post-consumer wastes, and so on. Thus, performing a mass balance of the sectors and the whole system a verification of the model can be obtained. Figure 12-A shows the material system dynamics between 1972 and 2014, based on the logistic regression data from the statistical data and model generated data. A logical behavior and development of all the variables that describe the AMS is seen, which matches to the expected reaction of such system. Further, figure 12-B describes the mass balances of the whole material system and the modeled sectors. The mean values approximately to zero for every sector shows a low discrepancy of the mass balance along the whole simulation. This also suggests a very good stability and consistency of both exogenous and endogenous data in the model. With these results it can be concluded that the logical structure and expected behavior of the model are appropriate for the purpose of this work. Further it also provides a solid base for the estimation of future state of the AMS under scenario approach.

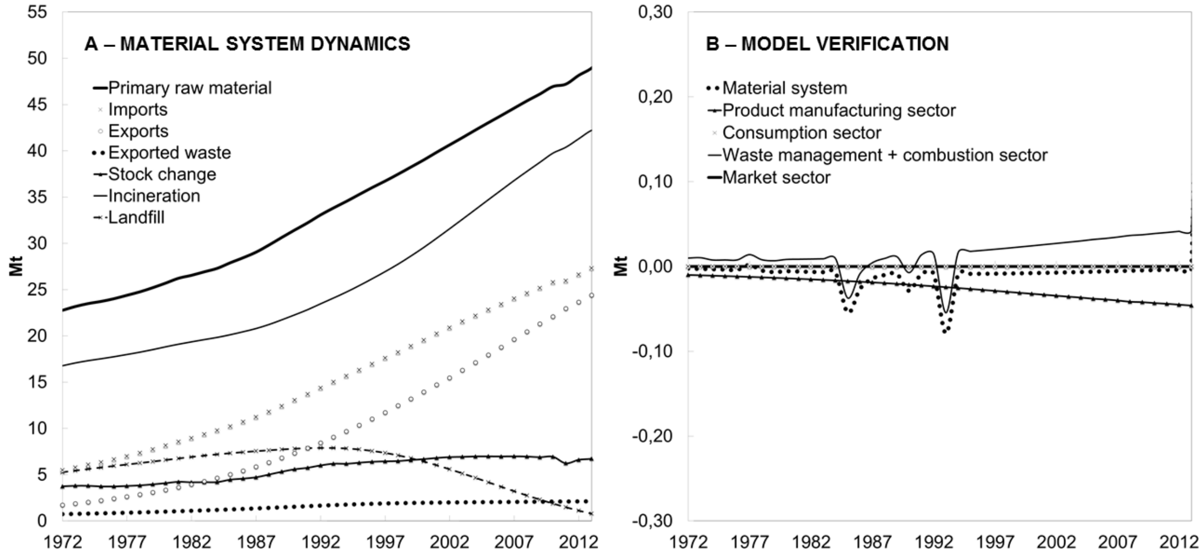


Figure 12: Mass balance verification of model dynamics with historic data

### 3.4.2. Calibration

Despite the logical behavior and development of the AMS, it is necessary to have a proper knowledge of the changes and uncertainties in the parameters and input variables used for the dynamic modeling (Laner et al., 2014). Although, some of these data are found directly in the literature with relative low uncertainty, some others are approximations or have been obtained from estimation methods, where the uncertainty is much higher. Historical values for population, per capita consumption of material goods, market share, foreign trade, and waste management recovery rates are retrieved from statistical databases, scientific reports, articles and in some cases web pages. From an engineering perspective, uncertainty is the lack of knowledge about the real value of a quantity. Despite the constant improvements of measuring devices, availability of big data sources or accumulation and verification of information of all kinds, uncertainty is always present and it is an innate property of quantifiable values. The reliability of results from the model depends not only on the modeling structure and algorithm, but also on the quality of the input values (Rechberger et al., 2014). For instance, modeling of historical and future data uses information from statistical national and global databases. Statistical databases are regularly subjected to national governmental entities and in the case of European databases, such as EUROSTAT, are discriminated by countries. At a national level, comprehensive databases are also available, such as the German Statistical Office (DESTATIS). This system structure is advantageous for the development of a dynamic stock-flow model as data quality and availability is very satisfactory.

However, due to the lack of systematic and complete information, missing historical data was calculated following logistic regressions of the available data to create continuous data series. To evaluate the effects of this knowledge and information gaps, a calibration procedure, that is an uncertainty analysis using a Monte Carlo simulation, is therefore performed. This enables the understanding of the effects in the parameter range in agreement to the output results and available statistical or measured data. Because of the large number of parameters, the calibration procedure is a trial-and-error systematic approach (Jorgensen and Bendoricchio, 2001), where the most relevant variables and parameters are evaluated. Input variables like per capita consumption, population dynamics or in-use lifetime changes were evaluated.

Uncertainty is present both at the input data and correspondingly in the output results of the model, which is coped with a thorough uncertainty analysis of the input variables and following scenario approach. The uncertainty for input variables has several sources due to its heterogeneity such as data inaccuracy, data gaps, modeling simplification or stochastic, among others. Other sources of uncertainty compile epistemological, choice or temporal sources, which do not have a strong impact in the quantifiable uncertainty. Uncertainty analysis is a measure of this quality upon the basis of continuous or discrete probability distributions. Input data uncertainty has been defined with statistical data, expert based approximations with or without probabilistic distributions, assumptions or a combination of all three. The lack of information about the standard deviation or parameters of the input variables is compensated using a shape-based distribution. Because the uncertainty of the input data is not strictly bounded to any model equation, that is, no standard deviation is possible to be estimated, a non-parametric (also called empirical) univariate continuous left-right bounded probability distribution is selected. Further, since the standard deviations from the input data are in general not known the use of a normal distribution is limited. Therefore, the uncertainty analysis is performed on minimum, maximum and mean information of the input data. Continuous distributions such as the triangle or the PERT distributions (see figure 13) are the most suitable in this case. The complete evaluated input variables and uncertainties for the model are shown in table B.1 in Annex B, were a total of 49 parameters were considered.

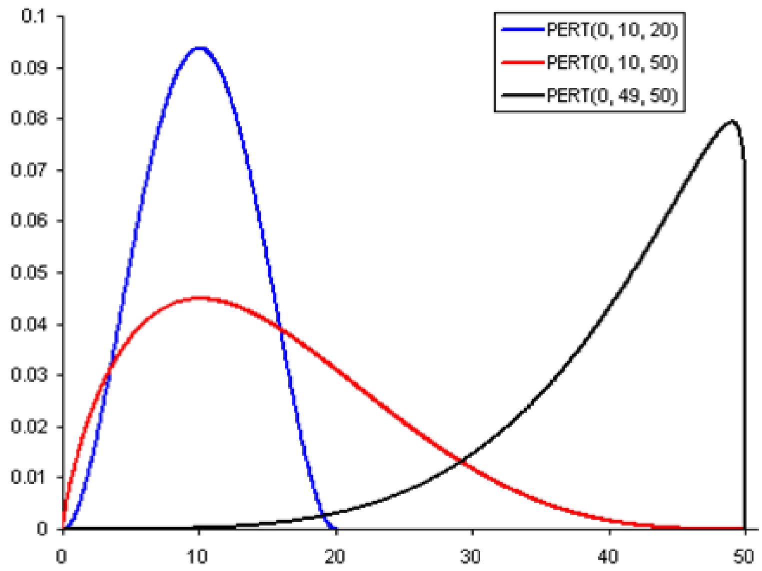


Figure 13: PERT distribution for uncertainty analysis (Source: Vosesoftware.com)

### Monte Carlo Simulation

Monte Carlo simulations (MCS) evaluate multiple parameter variability in the model processes and outputs. A MCS systematically, and randomly, varies the selected input variables simultaneously in a delimited value range, constrained by a probability distribution. With the input uncertainty the propagation of uncertainties produces a distribution of values in the outputs. Thus, a range of possible values, between the defined minimum and maximum, are used as input data in the modeling process. This is a common configuration which is assigned to a selected probability distribution, depending on the nature of the variable and the knowledge of its properties. In this case, as mentioned above, the PERT distribution was chosen.

The histograms in figures 14-A to 14-F exemplifies the results of the MCS for paper material group and illustrate the results of the six main output variables: (1) primary raw materials, (2) secondary raw materials, (3) domestic demand, (4) stock dynamics, (5) waste outflows and (6) carbon emissions. The spread of the results data from the median is quantified within the first two deciles (±10%) and the first two quartiles (±25%) as described in table B.2 in Annex B. Normal distributed trends are seen in all cases, as the values of skewness and kurtosis show, with a higher tendency in having wider peak around the median. The MCS also shows that in most cases results lay within the first two quartiles. Results for the other material groups, wood and plastic are found in Annex B.

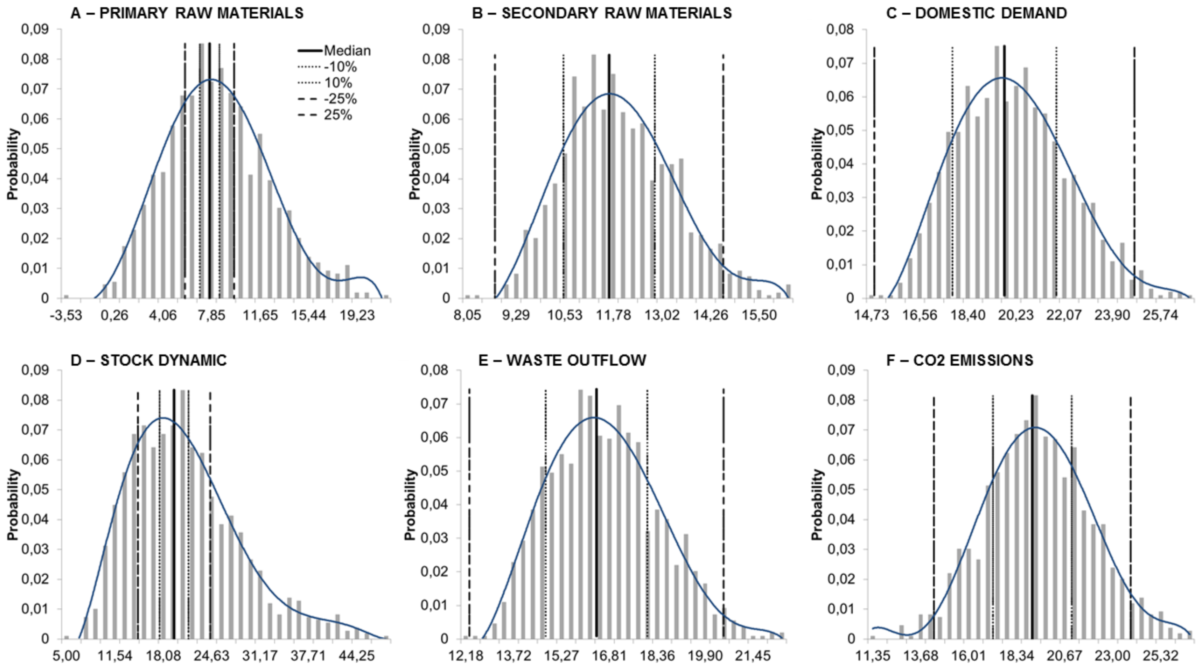


Figure 14: Results for output factor from a Monte Carlo Simulation (MCS) for paper products

### Quantitative Sensitivity Analysis

The sensitivity analysis provides a hint for the calibration of the model as it helps to identify the elements that are most responsible for an acceptable model performance. As mentioned above, these elements are parameters, assumptions, structures and so on, included in the model (Saltelli et al., 2002). A quantitative sensitivity analysis (QSA) provides confidence about the results of the model. It is especially useful by environmental studies, as the dynamics of these systems can be altered with very small changes and provides a solid basis for decision making when considering environmental threats.

$$\boldsymbol{\Gamma_x} = \frac{\gamma_x \sigma_x}{\sigma_y} \tag{29}$$

$\boldsymbol{with},$
$\boldsymbol{\Gamma_x}$ = $\boldsymbol{Standardized\ linear\ regression\ coefficients}$
$\boldsymbol{\gamma_x}$ = $\boldsymbol{Linear\ regression\ coefficient}$
$\boldsymbol{\sigma_x}$ = $\boldsymbol{Standard\ deviation\ of\ input\ factor\ x}$
$\boldsymbol{\sigma_y}$ = $\boldsymbol{Standard\ deviation\ of\ output\ factor\ y}$

On the other hand, QSA is a strong tool for answering "what if" questions under modeling approach, as the variability in the input factors allows an exploration of the system model and the variables that should empirically be further researched. From a model perspective, QSA assesses the relative importance of the input factors, and aims to answer what input uncertainty has larger effects in the output uncertainty; and what input variables should be considered at most to reduce the variance of the output results (Saltelli et al., 2002). Because of the diversity of variable units, the regression coefficients are standardized using equation (29) based on the standard deviations obtained in the MCS of both input and output factors. The standardized regression coefficients (SRC) indicate the sensitivity of the outputs with respect to its input factors in terms of standard deviations (Saltelli et al., 2002). Although every single variable provides a SRC, not all have meaningful contributions to the model, some are statistically significant in the changes of the input variable. A further explanation and results are provided in Annex B.

The SRC shown in figures 15-A to 15-F exemplifies the QSA results for the paper material group. It indicates the input variables with larger effects over six selected output factors. Positive values indicate a proportional effect, while negative values an inversely proportional one. Changes in service-based lifetimes, in manufacturing and recycling efficiencies and demands in foreign markets, seem to have high sensitivity within the model. This leads to some main points: (1) the uncertainty of these input factors should be as lowest as possible and it should be vary in short ranges, (2) a change in the model structure and calculation process could be made in order to reduce the dependency of some of these variables in the whole calculation process, (3) with a lack of knowledge of the real values these variables should be a constant as possible. On the other hand, is perceived a low sensitivity in the lifetime of commodities, most likely caused by their very long lifetimes. Although it is clear that the model is not fully linear, many of the individual inputs do have a linear behavior. In consequence these regressions can suggest the sensitivity of the variables. Nevertheless, the square-of-fit value (R2), as shown in table B.3 in Annex B, was also taken into consideration as a measure to observe the linearity of the regression, as well as the capability of prediction of outputs. This point might have small relevance on the uncertainty and sensitivity analysis; however it provides criteria for future use of the obtained regressions.

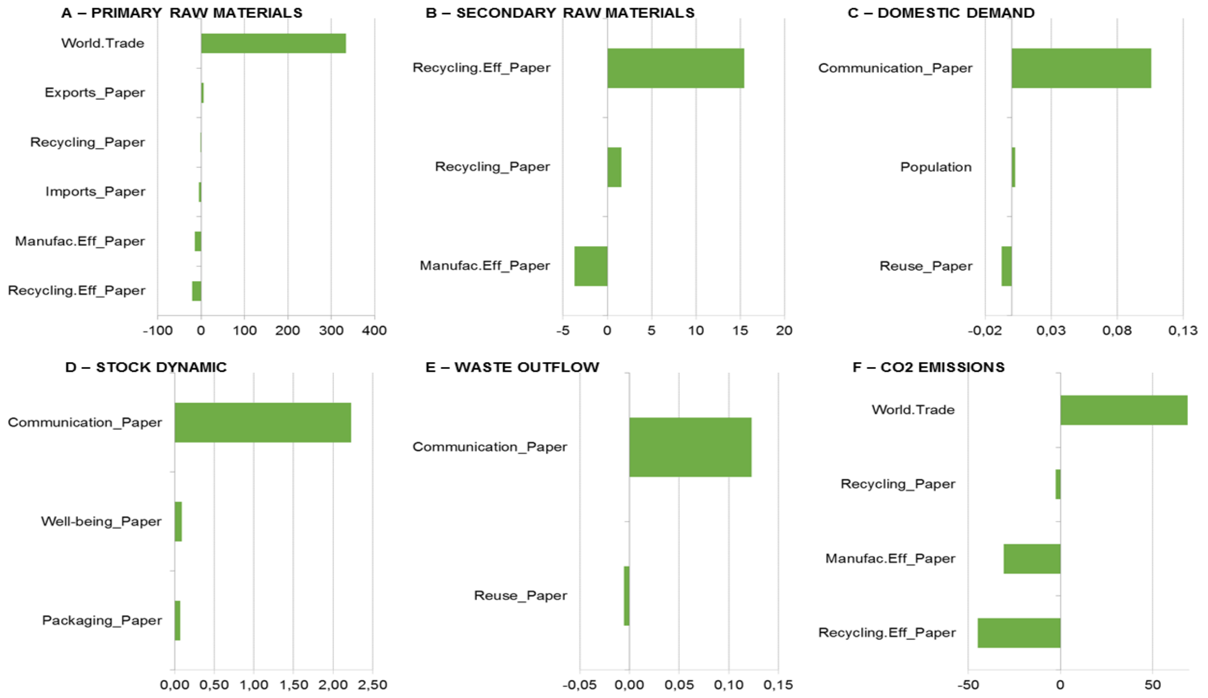


Figure 15: Variation of standardized linear regression coefficients of input variables for sensitivity analysis on paper products

The presented outputs cover the whole range of results the model is capable of estimating: from primary and secondary raw materials, to expected waste outflows from different goods and lifetimes, to the change of stocks and effects of consumerism in the evaluated anthropogenic material goods. As expected population changes, world market or manufacturing efficiencies showed a higher impact in the output results, and defined which input variables should have the lowest uncertainties. Under this perspective high sensitive input variables should have minimum but significant changes, while low sensitive variables may have wider variations when necessary. Further some values from the baseline scenario are either minimums or maximums. Keeping this information in mind and according to the sensitivity results, the parameters and variables are calibrated and adjusted to obtain plausible and realistic current and future results. The complete list of SRC is summarized in table B.3 in Annex B, for every evaluated output factor of the model.

### 3.4.3. Validation

As one last step in the validation of the model, the output results are compared with independent historic and available data. With the validation a general trust of the model is gained for an appropriate description and prediction of the system in past and future periods. In other words, it provides a picture of the reliability of the model behavior (Jorgensen and Bendoricchio, 2001). For the validation procedure it is necessary to compare data which was not used for the calibration or the verification procedures. The results and analysis of the validation step are discussed in section 5.4 in chapter 5.

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# 4. The German context of three main carbon-based industries

The model discussed in chapter 3 provides a tool for describing and characterizing an anthropogenic material system (AMS) under an economy-wide approach. It is used for modeling carbon-based industries in Germany to evaluate and describe possible developments and dynamics of anthropogenic carbon flows and stocks. It will also provide foreseeable opportunities for the efficient and environmental material management of carbon-based products, post-consumer wastes and related carbon emissions within the AMS, and it gives possibilities for understanding circularity of carbon-based materials in the anthroposphere. Carbon-based industries rely on the element "carbon". This will be introduced and thoroughly discussed as a vital component for current needs within SEM.

## 4.1. Distribution of carbon in material systems

Carbon (C) is one of the most important chemical elements on Earth present in both biogenic and anthropogenic systems. It is the building block for every organic substance and living organism on the planet. Additionally, it is a main driver and important component of final goods for the satisfaction of a large number of the present societal needs and development with energy and material purposes. In many industrialized countries one of the largest material flows in an economy-wide perspective come from biomass and fossil fuels origin, showing a non-trivial amount of embodied carbon in products and materials (OECD, 2010a). Due to the potential accumulation of anthropogenic carbon stocks in the material system, a hidden and unrealized source of carbon can be released in the atmosphere with impacts in climate change. Notwithstanding, these uses have effects in socioeconomic, technical and environmental contexts. In the latter, it has gained a negative reputation as a strong contributor for human-induced climate change (IPCC, 2006; IPCC, 2014). The distribution of carbon in material systems is described in carbon cycles. These takes place considering carbon flows and stocks driven through biogenic and anthropogenic systems.

### 4.1.1. Carbon cycles

Figure 3 in section 3.2 describes an interconnected economy-wide anthropogenic material system with the biogenic material system. This leads, of course, to a parallel relationship between the biogenic and the anthropogenic carbon cycles (Canadell et al., 2007), as carbon from the material perspective is directly integrated within the material systems. Nevertheless, understanding each cycle provides a clear perspective about the relevance and mutual dependence of both cycles. Thus, changes in the dynamics of one carbon cycle have effects on the other.

**Biogenic carbon cycle**

The biogenic cycle is described under biogeochemical processes. These processes are large-scale processes occurring in the Earth ecosystems like: photosynthesis, liquid-gas diffusion, respiration of living organisms and decomposition of matter (Rötzer et al., 2009; Smith et al., 2010; Singh and Bakshi, 2014). These processes are closely integrated for example by diffusion mechanisms between the atmosphere and the ocean, by decomposition mechanisms from dead biomass to the lithosphere and atmosphere, or by respiration and photosynthesis processes between the atmosphere and living biomass. Thus, carbon flows through the atmosphere, the biosphere, the ocean and the lithosphere in multiple physicochemical states, and accumulates as biogenic carbon in the Earth crust in form of coal, standing or dead biomass, crude oil, gas reservoirs, wildlife, human population, among others. Through these mechanisms the biogenic carbon cycle finds a balance. At the biogenic level while some of the carbon pools appear both as carbon sources and carbon sinks like the atmosphere, the oceans and the standing vegetation, others such as fossil fuels, limestone and dolomite deposits are net carbon sources. In the terrestrial vegetation, the main carbon pools are living biomass of trees and surrounding vegetation, plus the dead and soil organic matter (Gibbs et al., 2007). Within the growing vegetation, gaseous carbon is converted and stored in solid carbon-based fibers by the natural process of photosynthesis, which removes $CO_2$ from the atmosphere and sequestered it in the growing biomass, wood and others herbaceous raw materials, becoming a carbon sink.

From these mechanisms, the carbon contained in the oceans ascends to circa 40,000 Petagrams of carbon (Pg C) and in the marine sediments and sedimentary rocks exceeds 60 million PgC (Smith et al., 2010). Soils contain 1500 PgC, nearly twice the amount of carbon in the atmosphere and roughly three times the amount of global biomass (Smith et al., 2010). For fossil fuels, rough estimates of the global underground and superficial mineral carbon deposits like brown and black coal, crude oil or natural gas, are in the order of 4000-5000 PgC, though this storage are highly uncertain. These large amounts of stored carbon in the biosphere are a product of the biogenic carbon cycle, which has been driven by the solar input. Since the 18th-century's industrial revolution, changes in this cycle have been perceived caused by anthropogenic activities with a net emission of carbon dioxide coming mostly from the mineral carbon deposits. Carbon dioxide emissions has balanced off the energy exchange between the biosphere and outer space by trapping the reflected heat from the solar energy input and modifying global temperature and creating an environmental burden in various global ecosystems (IPCC, 2014).

### Anthropogenic carbon cycle

The biogenic carbon reservoirs have been exploited or harvested by humankind as a source for energy and raw materials to fulfil considerable requirements and services in the anthroposphere. These uses creates a threshold, where biogenic carbon can be denoted after certain point as anthropogenic, providing carbon-based materials like oil, coal or wood for manufacturing processes and transformed into an extensive amount of goods and products used within AMS. Further, under a specific in-use lifetime each manufactured good is used and finally discarded as post-consumer waste. The in-use lifetime of goods, driven mainly by consumption behaviors and final use of the product, fosters material accumulation or formation of anthropogenic carbon stocks expressed in capital stocks (like built environment and infrastructure) and short- and long-lived consumer stocks. Thus, the anthropogenic carbon cycle takes into consideration the use carbon-based materials and energy carriers within the anthroposphere, its use and discard with its potential carbon-related emissions (Gielen, 1997; O'Rourke and Connolly, 2003; Patel et al., 2005). In other words, it is based on carbon flow dynamic in the form of raw materials, final goods and post-consumer wastes.

## 4.1.2. Material and energy carbon uses

The main uses of carbon are summarized in table 3 showing average annual volumes of carbon used in large industrial sectors in Germany in 2006 (Uihlein, 2007). This table gives an insight of the approximate current used volumes as well as its final uses mainly in the anthropogenic carbon cycle. The sectors "Private households and consumption" and "Manufacturing industry" are one of the largest in volume with 134.0 Mt and 214.1 Mt, respectively, with high use in material purposes. This indicates the main sectors where anthropogenic carbon stocks are located. On the other hand, the use of carbon at the energy sector is extremely quick and carbon stocks are not built at all.

Table 3: Main carbon-intensive industrial sectors and use in 2006 in Germany, Mt according to Uihlein (2007)

| Sector | Mt C | Material use | Energy use |
|---|---|---|---|
| Energy | 95.6 | 0% | 100% |
| Agriculture and forestry | 207.2 | 99.2% | 0.8% |
| Private households and consumption | 134.0 | 39.0% | 61.0% |
| Manufacturing industry | 214.1 | 79.8% | 20.2% |
| Traffic and Transport | 19.6 | 0.5% | 99.5% |
| Waste management | 10.8 | 32.4% | 67.6% |
| Mining and raw materials | 2.7 | 59.3% | 40.7% |

The relationships between both cycles (biogenic and anthropogenic) are seen by the use of carbon in some sectors. The carbon intake from the atmosphere in growing biomass reflects the partially total material or non-energy (Weiss et al., 2008) use of the "Agriculture and forestry" sector, as its major interest is the production of timber and food. The same is seen in the "Mining and raw materials", where non-renewable resources (geological carbon reservoirs in the form of fossil fuels, coal, and peat, among others) are exploited. On the other side, carbon emissions are originated by the energy use in all sectors, especially the "Energy" sector, the "Traffic and transport" sector and the "Private households and consumption" sector. At the "Waste management" sector carbon is also potentially released to the environment in form of GHG emissions (Pickin et al., 2002). From table 3, it can be deduced that many industrial and manufacturing processes require carbon-based primary raw materials from renewable and non-renewable sources, as well as secondary raw materials coming from anthropogenic sources to satisfy consumption needs.

Additionally, the way carbon is present and used within the biosphere and anthroposphere is illustrated in a qualitative distribution in figure 16. This figure summarizes carbon flows and stocks at the biogenic and anthropogenic level under a two-level spatial distribution and a two-level end-use perspective. Thus, the figure can be divided into four quadrants. The quadrants located at the left represent the biosphere where most of the primary raw materials and natural sources are present. The quadrants found at the right side describe the anthroposphere, where processed materials and consumption goods are mostly dominant.

The shaded area (anthroposphere) has the largest influence and main focus of this work. Here, carbon use is materialized with consumer and capital goods, which provide a specific service for the satisfaction of human needs. The upper-right quadrant of figure 16, presents several material uses of carbon-based materials. With these, anthropogenic needs for packaging, transport, communication, living spaces or well-being can be fulfilled. The lower-right quadrant illustrates the potential energy carriers at the anthropogenic level used for heating and well-being in living spaces coming from industrial and waste treatment processes. In terms of energy uses, the high calorific value of carbon is appropriate for combustion processes for heat and electricity generation. Here, the carbon transfer from sources to sinks is relative fast, as the oxidation of carbon to gaseous state takes place in very rapid processes avoiding the building of carbon stocks.

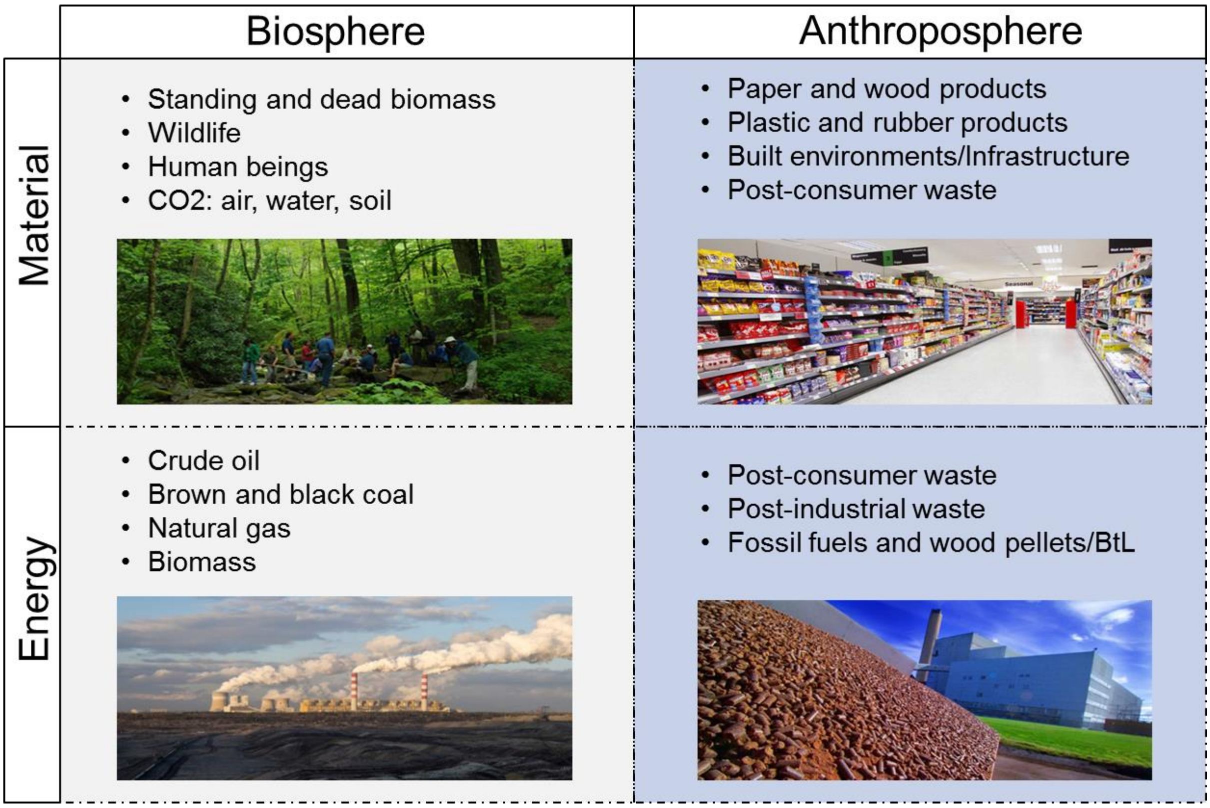


Figure 16: Qualitative carbon distribution and use in the biosphere and anthroposphere (Source of images: https://www.google.de/imghp)

Carbon stocks are the absolute quantity of carbon present in a carbon pool at a specified moment coming from any carbon-based material or product that has permanence longer than one year (Elshkaki et al., 2004). With this perspective, energy uses of carbon are mostly considered flows, while the material uses are prone for stock building. In other words, the upper quadrants in figure 16 describe potential carbon stocks, while the lower quadrants carbon flows. Further, carbon stocks can be categorized in biogenic and anthropogenic stocks. Biogenic carbon stocks constitute all possible stocks available in lithosphere and Earth's surface not transformed by human beings: standing forests, oil reservoirs, peat, and so on. On the other hand, anthropogenic carbon stocks represent the group of manufactured products from carbon-based materials available in the anthroposphere for human use like paper, plastics and wood. Anthropogenic carbon stocks derive from natural carbon stocks. An important characteristic of carbon stocks is their capacity of storing or releasing carbon, when released mainly in the form of carbon dioxide ($CO_2$), making them potential carbon sinks and carbon sources, respectively.

### 4.1.3. Threats and challenges of carbon in anthropogenic material systems

Anthropogenic carbon flows and stocks dynamics contribute to potential and relevant environmental concerns, like global warming or resource scarcity. These are reflected, for instance, on the future allocation of carbon-based post-consumer waste and corresponding carbon emissions at the end-of-life processes (Cherubini et al., 2011), or the pressure of raw material supply that will increase dramatically in the future (UNEP, 2010; Giljum et al., 2014), but could be partially fulfilled with secondary raw materials. As discussed above, carbon emissions have become a main topic in political agendas and industries. The European Union and each of its members have set reduction targets from carbon emissions to cope this global problem (EC, 2015c). In 2007, for example, the German government defined through the "Integrated Energy and Climate Program" a reduction of 40% of the national carbon dioxide emissions by 2020 compared to the emissions of 1990; followed by a reduction of 55% in 2030, 70% in 2040 and 80-95% in 2050 (Wilke, 2013). In 2014 with a total carbon emission of 912 Mt $CO_2$-eq, Germany reached a reduction of 27% compared to 1990 (Wilke, 2013). While most of the origin of emissions comes from the combustion of fossil fuels for energy demands (over 80%) and industrial processes (7%), another share is originated in the agricultural sector (6.5%) and the waste management sector (1.2%) mostly from material uses (Wilke, 2013). Despite the fact that most of the carbon emissions are energy related (and seen as flows inside an AMS) the evaluation of potential emissions from carbon stocks (as temporary carbon sinks) should not be neglected. Carbon-intensive material industries manage large volumes of carbon-based materials in the anthroposphere for material purposes, leading to a stock building in the AMS.

The carbon emissions potential from anthropogenic activities in the atmosphere is an environmental concern and a threat to the sustainability of current lifestyles. Recent scientific reports confirm the effects of carbon emissions as a driver for a human-induced climate change (IPCC, 2014; Worldwatch Institute, 2015). While carbon emission from energy-related activities are commonly addressed, attention to the carbon emissions from material-related activities must be drawn, as products from carbon-based materials like plastics, paper and wood store or binds carbon temporarily (Gielen, 1997; Rüter, 2008). These carbon sinks release carbon mostly from discarded material goods after waste incineration or energy recovery mechanisms in waste treatment processes. Also, the carbon dioxide ($CO_2$) and methane ($CH_4$) emitted by natural decomposition processes in harvested forests, by gasification or in landfilling facilities can be seen as emissions from material uses (Barlaz, 2006; Ximenes et al., 2008). In many industrialized countries one of the largest material flows in an economy-wide perspective come from biomass and fossil fuels origin, showing a non-trivial amount of embodied carbon in products and materials (Kohlmaier et al., 2007; Tonn and Marland, 2007; Rüter, 2008; Köhl et al., 2009). Due to the accumulation of anthropogenic carbon stocks in the material system, a potential (and unrealized) carbon source is present. Evaluating carbon-based products at AMS complement partially this unknown source gaps.

The current society has taken advantage over the physical and chemical properties of carbon and has used it in a wide number of sectors inside the anthroposphere, as shown in table 3, for energetic and material purposes, becoming one of the main elements and drivers in its development. Considering the importance of carbon in the development and functioning of anthropogenic activities, carbon-intensive material industries contribute significantly in the course of present and future social, economic and environmental issues. Having this context in mind, the case-based study comprises the region of Germany enclosed a global scene. As described above, the model studies the material "carbon", with the evaluation of three relevant carbon-intensive material industries inside the German boundaries, namely, (1) the pulp and paper industry (from now on called the paper industry), (2) the wood and processed wood-based product industry (from now on called the wood industry) and (3) the polymer and plastic processing industry (now referred as plastic industry). The rubber industry is an additional carbon-based industries present in Germany mainly concentrated on the processing of natural and synthetic rubber for the production of vehicle tires and technical elastomers products. Because of its narrow product palette and applications, it is combined appropriately within the plastic industry in the model. The industrial sectors use carbon to develop a complex network of products and derived services with multiple applications and uses. For example, paper products range from technical books to toilet paper; wood is present in furniture or construction; plastics are used from electronic equipment to simple bags; other materials like rubber for automotive tires, also belong to manufactured carbon-based products. This constellation appeals to the understanding of the dynamics of carbon-based industries and material systems in the anthroposphere to gain urgent knowledge in sustainable carbon management. An analysis of the most relevant industries at a national level will be made in detail in section 4.3.

## 4.2. Context of the German anthropogenic material system

A second important pillar before discussing in detail the carbon-based industries in Germany contextualizes these industries from an economy-wide approach. The description and evaluation of AMS are defined by the type of material (or materials) studied in a selected region (or regions). However, for modeling easiness and data availability, regional studies and analysis are often confined with national limits. At a regional level, the material systems are dependent of both national and international trends and perspectives and because of the complex trading network between economies, also a global context and trends have to be considered.

As indicated in chapter 3, a series of important socio-technical, economic and environmental factors determine the dynamic and development of the material systems in the anthroposphere. These are relevant trends that provide on one side, a solid basis for understanding current states of the national affairs, and on the other side, it elucidates possible developments of the economies on both national and international level. Examples of these trends are: demographics, consumption of goods and resources, innovation, urbanization, social movements, globalization, mobility, among others. Such trends are normally deep tendencies of change with notorious effects in politics, society and economy, as well as in science, technology and culture, both at an individual and social level. Within AMS effects are seen in stocks and flows dynamics and have the capacity to shift a whole material system and define future states in the AMS, for instance, a sustainable system or a collapsing one. For this reason the most relevant trends that can influence both national and international affairs in the AMS are discussed. This analysis gives a solid basis for understanding the state-of-the art of the region and provides a guide for sound retrospective and prospective analysis. Based on the trends shown below, relevant aspects that contextualize the AMS are described and serve as conceptual backbone for the scenario analysis.

### 4.2.1. Demographics

The historical context of the German demographics has an influence the development and dynamics of the AMS. Thus, the first factor to be considered is the demographics. Because of the reunification in 1990, the population of Germany changed officially from 62.68 million to 79.75 million in the term of one year (DESTATIS, 2015b). Despite the sudden population jump at the beginning of the 90's, the German population shows a strong trend to shrink with no signs of recovery (UN-DESA, 2015a). This phenomenon from a socio-economic point of view brings political and economic challenges to the country (VCI and Prognos AG, 2013). Therefore, a fear for labor shortage and a reduction of qualified personal (caused by the change in the population pyramid) combined with an aging of the population can be expected for the coming future. Further, Germany has been traditionally a country with low migration rate of nearly 1.24 per 1000 inhabitants (CIA, 2015). Notwithstanding, the 2015 immigration flow crisis of some hundred thousand refugees from the Near East and Central Asia might provoke a spike in the population trend, no real shifts can be expected. In fact, for the coming decades a net immigration between 100,000 to 200,000 persons might be the best guess (DESTATIS, 2015b). The German population in 2014 was about 80.76 million inhabitants (DESTATIS, 2015b) and it is departure point for the population forecast until 2055.

The possible population developments in Germany and the world are shown until 2100 in figure 17 (UN-DESA, 2015b). A strong declining trend is seen with the exception of some curves where the population remains more or less constant to current levels. In general terms, the shrinking population trend appears to be an irreversible process. Based on the result of these scenarios the most expected population values in 2050 are between 70 to 75 million and in 2060 between 65 to 70 million. On the contrary, the world population maintains in general a rising behavior for the coming decades. This indicates a permanent increase in demand of materials, food, services and wastes. The world population show signs of growth, especially in developing countries. The development is of course different along the regions of the world; regions such as South-East Asia or India will have faster growth rates, while Europe will face a slower dynamic (UN-DESA, 2015a). While in most developing countries population growth is experienced (with the exception of Russia with -0.6% per year), in industrialized countries the dynamic is weaker and even in some population is shrinking (Japan, Poland and, as shown above, Germany both with nearly -0.2% annually). On the other side, the developing countries will grow at an expected average global annual rate of nearly 0.9% per year (VCI and Prognos AG, 2013).

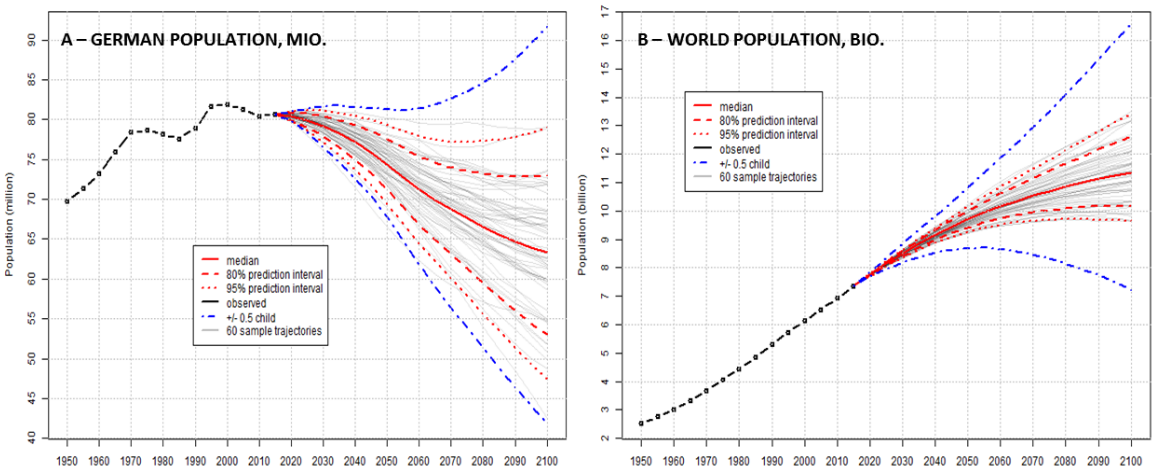


Figure 17: Expected development of the German and world population until 2100 (UN-DESA, 2015a)

Because of the sensitivity of this variable (as found in section 3.4) in the modeling of the material system dynamics the population of Germany before 1990 was defined as the sum of both West and East Germany. The reasons are first the inherent presence of an AMS in both regions. In both countries a societal metabolism is present where stocks and flows of raw materials, final goods and post-consumer waste have been taken place. This assumption also mitigates the impact of 10 million new consumers suddenly appearing. A sudden change in the population (if only West Germany is considered) disturbed the stock-flow dynamics and creates unrealistic changes in raw material demands and consumption. The second reason is the compatibility for the prospective analysis of the material system. In future stages waste and stocks belong to one single country. In other words, the former eastern Germany's post-consumer waste and built stock which in the future will become waste and secondary raw materials is now part of the Federal Republic of Germany for the coming decades.

### 4.2.2. Consumption of goods

From an economical perspective Germany shows still a strong and steady industrial and financial stability which will continue for some decades ahead. It is the fifth economy in the world, and Europe's largest, in terms of purchasing power parity (CIA, 2015). Despite the drawbacks of the 2009 financial crisis and the 2015 Euro-crisis, its economic strength has been was demonstrated with the fast recovery of the first crisis, where the country's gross domestic product (GDP) reached pre-crisis levels in less than four years (World Bank, 2015) and currently as a result of the current Greek-crisis, the country has improved its competitiveness among the European countries. Although the past and current economical dynamics have been much steeper, it is expected that the German economy will continue to grow at an annual average rate of 1.3% at least until 2030 (VCI and Prognos AG, 2013). Thus, despite this financial fluctuation, Germany maintains a strong economic momentum that has boosted the industrial sector, including the paper, wood and plastic industries among other industries, as it will be shown below (CIA, 2015).

Under this good economic environment, Germany holds one of the highest per capita consumption values of carbon-based goods worldwide (Stuchtey and Below, 2015). It is the fourth largest paper consumer in the world (FÖP and Ökopol, 2013; Fleiter et al., 2012), the largest timber (Mantau et al., 2010b) and plastics (Consultic, 2013) consumer in Europe. For instance, the German pulp and paper per capita consumption is almost fourfold the world average (VDP, 2015), meaning an average world consumption of around 60-65 kg/cap in 2010. Similar differences between domestic and world volumes are seen in the per capita consumption of wood and plastic products (FAOSTAT, 2015; Vassiliadis, 2014). The consumption volumes in Germany have shown rising figures and it is presume to maintain an increase trend, though with a slower dynamic, for several demographic, economic and socio-technical factors (Leismann et al., 2012; VCI and Prognos AG, 2013; Schiller et al., 2015). First, the declining population and reduction of working force increase the per capita net income, increasing the purchasing capacity. As discussed above, it is expected a reduction of almost 6.5 million persons between the age of 15 and 64 years by 2030 (DESTATIS, 2015b). Second, as the population ages, a larger group of retired persons will conduct to a higher per capita consumption. Third, in the long run the economic stability and consequent low interest financial rates shall give confidence to consumers and increase the household consumption. The growing domestic demand is also driven by technical innovations. It is expected within the industries an improvement in energy efficiencies, a deployment of renewable energies under the *Energiewende* policy (EEG 2014) and a rising awareness in environmental-friendly consumption (Leismann et al., 2012; VCI and Prognos AG, 2013) will also promote the increase in per capita consumption. According to studies it is expected an increase between 10% and 42% of the current consumption rates (VCI and Prognos AG, 2013).

At the international level, the consumption of goods worldwide will definitely increase significantly specially in the Asian countries. Carbon-based products have all increasing dynamics, although wood products are facing a relative slow dynamic worldwide (FAO, 2009) as the per capita consumption is stagnating (see figure A.1 of per capita consumption regressions in Annex A). Final carbon-based goods like vehicles components, electronics, and commodities have a strong potential in these markets, as a larger low-income population is increasing its purchasing capacity. Because of its export-oriented economy, Germany will benefit from the economic growth of developing countries. The world export trading is expected to grow annually on average 4.2% (WTO, 2015) and play a significant role in the evaluated material system.

### 4.2.3. Resource availability and industrial innovation

The potential scarcity of natural material and energy resources for some technologies and manufacturing processes worldwide affects constant supply and security of raw materials (Chen and Graedel, 2012; Graedel et al., 2015). Resources like water, land, metals or oil are facing environmental pressures at exploitation and distribution sites. On the other side, tangible changes in ecosystems, like increase of dry or rainy seasons, extreme temperatures, spread of tropical diseases to septentrional regions, among other examples, are gaining momentum globally (Worldwatch Institute, 2015). This situation has led to an increase in the awareness of environmental conservation and protection and has included terms like circular economy, industrial ecology, climate change and carbon emissions at political, social and academic spheres. The latter is seen as the cause for many real environmental problems, so political and economic strategies (like, carbon taxes, emissions trading, increase in energy and manufacturing efficiency, industrial symbiosis, or deployment of renewable energies) are being implemented to cut carbon emissions, as uncertainties for a new economic reverse are present (Worldwatch Institute, 2015; IPCC, 2014). Although Germany have strategic plans to secure sufficient and raw materials of mineral and non-mineral resources (Stuchtey and Below, 2015), like carbon-based materials, in the coming decades, these global effects cannot be ignored.

As a result of the declining population, the increase of productivity and efficiency are determinant to maintain an active economy and society's stage of development (Schebek et al., 2015). Notwithstanding, the improvement of both energy and process efficiencies of the German manufacturing industries are also closely related to the growing scarcity of resources. This might force in some cases to alternate the raw material mix for specific products; for example, plastics from renewable resources, or engineered wood-plastic matrices. Coping with the scarcity of resources has also been made with efficient solid waste management policies. As a consequence, Germany has in 2013 one of the highest recycling rates in the world for relevant carbon-based materials, paper with 78% (VDP, 2013a), wood with 15% (Mantau et al., 2010b) and plastics with 35% (Consultic, 2013). Both rates could be optimized according to future energy and material requirements and taking into account a climate change perspective. For example, in the last twenty years the chemical industries (including the plastic industry) have reduced the waste production in almost 80% but it seems that the potentials for resource protection are literally exhausted. Therefore, a further action for improving the material throughput is through technological or industrial innovation, and some energy decoupling has been achieved since 1990. While the energy consumption has decreased by 20%, the production has increased by 60% (VCI and Prognos AG, 2013). Nevertheless, with current technologies the decoupling of production and raw material consumption is, in the short term, not feasible. It is expected that global technology innovation (Schebek et al., 2015) will contribute to strengthen the economic global system and cope future GHG emissions.

### 4.2.4. Foreign trade

Germany is an export-oriented economy, where the foreign trade play a fundamental role in the AMS, including carbon-based raw materials (Stuchtey and Below, 2015; ETTF, 2011). The supply of wood, have been shifting to foreign markets in recent years, as the domestic supply has shortcomings. This shows an increase in the vulnerability of domestic extraction of carbon-based raw materials. Looking first at the import situation, the country lacks of domestic or indigenous fossil-based raw materials and are in large extent imported (WTO, 2015). Thus, Germany depends heavily in imports for manufacturing of plastics, rubber and additional fossil-based products like paints, lacks, additives, fuels, and so on. On the other hand, the flow of wood resources to and fro Germany is concentrated almost within the European area with nearly 80% of this trade takes place (Mantau et al., 2010a; ETTF, 2011). Until date, the raw materials supply for the carbon-based material industries is of low concern and risk to the manufacturing sector, though the imports will remain in very high levels for the coming decades. Even in the case of renewable resources, say plant and animal origin, although lower than fossil fuels, imports are still around 60-70% (OECD, 2010a).

On the other side, the European Union is its most important export partner of Germany, and this is expected to remain as so. In fact, the weakening of the European economy has given to the German exports a stronger significance (CIA, 2015). Germany as a world leading exporter had an approximate share in 2014 of nearly 7.72% of the exports worldwide (WTO, 2015) despite the fact that, foreign trade in most of the cases happens with neighboring countries. For instance, France is by far the largest trading partner of Germany. With this premise, exports of primary and secondary raw materials and of finished goods within the European countries constitute nearly 68% (Stuchtey and Below, 2015). Almost 57% of the shares of goods reach members of the European Union, while following in importance the Asian market accounts for 16% and the North American market with 12% (DESTATIS, 2015a). Exports will reach fast growing markets, with increasing per capita consumption rates, while imports will be present in an almost saturated market with a slower consumption dynamic.

### 4.2.5. Urbanization

Urbanization is a driving force for the construction sector where large quantities of raw materials are required to maintain the urban functionality. It is a fundamental element in the development of the AMS as many of the services and activities takes place within residential and non-residential buildings, and also infrastructure. The term urbanization is to some extent divergent, as for some urbanization represent all the areas where human action has taken place, while other prefer to differentiate between urban and rural areas. Here the term is understood as the effect of creation of cities or densely populated areas. The degree of urbanization in Germany is around 74% and it is expected to maintain similar levels in the coming decades (CIA, 2015). Because of the expected declining population, a growing volume of abandoned urban dwellings and non-residential buildings might be seen (Schiller et al., 2015). Of course, at rural areas in Germany this phenomenon is also expected. Under such situation and considering the need of extraction of mineral and non-mineral raw materials, abandoned structures and infrastructures are to become potential sources of raw materials specially metals and mineral sources.

At a worldwide level, growing urban areas is a phenomenon that affects primarily the developing countries, with moderate influence within the developed. In developing countries the increase of income of certain groups leads them to become middle-class. Urbanization then drives the migration to cities, increases the use of vehicles, and promotes a higher flows of materials to concentrated spots.

## 4.3. Carbon-intensive material industries in Germany

Several key industrial clusters, that play a significant role in the national economy, depend largely on the use of carbon-based materials (Uihlein, 2007). Carbon-intensive material industries, shown in table 3, rely on raw materials with high content of carbon as their principal energy and/or material source required for proper process operation and keeping high market competitiveness. Carbon-intensive raw materials are mainly oil, coal and wood, with all its derivatives like gas, fuels, paper, plastics, synthetic rubber among others, used to manufacture a wide and diverse pallet of products, that fulfil different services and needs of the society. From a material perspective and for the study of anthropogenic flows and stocks in material systems, the paper and wood industries, as well as the plastic and rubber industries contributes to the anthropogenic flows and most determinant to stocks building, as these industries can provide short and long lasting goods and products used for consumer and capital stocks. Within the electricity and heating sector a clear high demand on materials coming from these carbon-based raw materials is required, which used as energy carries are seen as purely carbon flows. Plastics wastes are now used as alternative energy sources, which have increased its incineration volumes over 60%. Wood products are also preferred for this purpose. As mentioned above, the case-based study evaluates three relevant carbon-intensive material industries inside the German boundaries. These are the paper industry, the wood industry and the plastic industry, including the rubber industry.

### 4.3.1. Paper industry

The German paper industry (or more precisely the pulp and paper industry) enjoys a privileged position within the global arena. It is the largest European paper industry and the fourth largest in the world (FÖP and Ökopol, 2013; Fleiter et al., 2012). In 2014, the pulp and paper domestic production reached 22.53 Mt with a per capita consumption of 247.0 kg/cap (VDP, 2015). The German society is one of the largest pulp and paper consumers in the world (VDP, 2015; VDP, 2013a) with almost four-fold the global average value (55-65 kg/cap) and it is estimated to have a volume of nearly 410 kg/cap in in-use stocks (Cote et al., 2015).

The growth of the German paper industry in production, consumption, imports and exports for the period 1950-2013 is shown in figure 18 (VDP, 2013b). The industry had a continuous and rapid growth, especially in the period between 1985 and 2005. Now it shows signs of deceleration and possible economic stagnation during the coming decades. In the last ten years a levelling off in domestic demand and production, as well as the foreign trade is perceived. It is a challenge for the whole European paper industry as the phenomenon is a response, on one side, of the reestablishment of manufacturing processes in developing countries (FÖP and Ökopol, 2013), and on the other side, this backward situation is an effect of the recently financial crises. It also indicates a possible saturation of the paper needs within the German economy. Traditional paper uses are being replaced with other technologies and materials like plastics or metals, among others (Dispan, 2013b). For example, the increasing use of electronic media (paperless resources) to replace printed paper services (books, magazines, advertisement, newspapers, and so on) dropped the newspaper production by 9% and the graphic paper production by almost 5% in 2012 compared to former year (FÖP and Ökopol, 2013). The industry far from breaking apart is developing new applications and paper uses that will target well-being needs (Dispan, 2013b). In fact, according to VDP (2015), the falling trend has been compensated with the increase in production in the same year of hygiene paper (1.6%) and paper for technical and special applications (1.9%). Further, an increase in manufacturing capacity of hygiene paper in Germany has been reported (FÖP and Ökopol, 2013).

At a global level, the paper industry shows signs of growth. It is estimated that the production of paper will increase between 1.8 to 2.5% annually until 2030 (VCI and Prognos AG, 2013). The demand of the paper industry worldwide will reach nearly 482 Mt by that year (PaperAge, 2006), with clear differences among the different global regions. While the consumption of paper will continue to increase in developing countries such as China or India, in developed countries possible stagnation or slight decrease in the domestic demand is expected (PaperAge, 2006). Considering the export-oriented economy of Germany, this appears to be an important solution for the German paper industry.

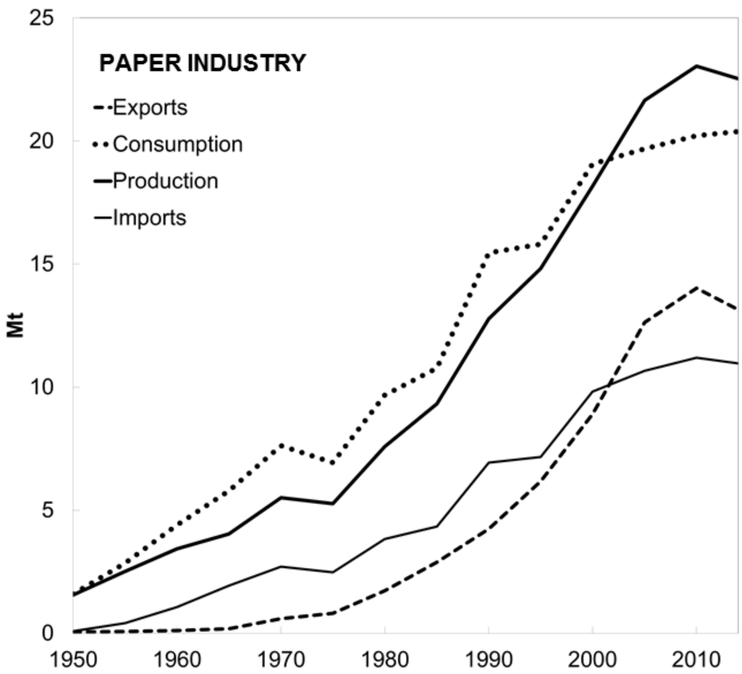


Figure 18: Development of the pulp and paper industry in Germany

Within the German market more than 3000 types of paper are found (PMV, 2013; VDP, 2013b) which can be grouped in four main types: graphic, packaging, hygiene and technical/special applications (Bilitewski, 2005). In 2014, the production distribution for these types were 38.42% for graphic uses, 49.04% for packaging, 6.38% for hygiene and 6.16% for technical or special applications (VDP, 2015), as illustrated in figure 19, where the volumes of required raw materials are also shown. The paper types can be constituted with an even more detailed classification, such as newspaper, wood-free coated and uncoated, wood-containing coated and uncoated, sanitary, base paper for photography, decoration, carton, among others. However, for the scope of this work the initial four-type classification under a service-oriented perspective provides a sound and sufficient description of the pulp and paper industry. Thus, paper products are classified within the services of communication (graphic uses), packaging and well-being (hygiene and special applications).

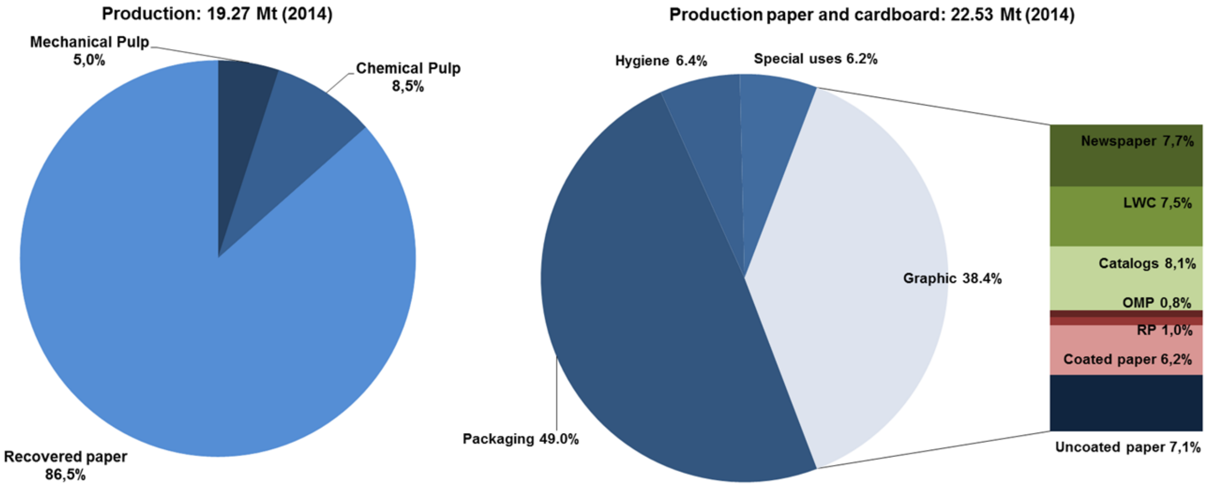


Figure 19: Production volume of raw materials and product groups in 2014 (VDP 2015)

As shown in figure 19, the largest production volumes are destined for packaging and graphic purposes having recovered paper (86.5%) as the main source for raw materials coming from secondary sources (Bilitewski, 2005; Bilitewski and Kügler, 2010; Kibat, 2012). The other used raw material is wood pulp obtained through two main processes: chemical and mechanical extraction (Martens, 2011c). The high recovery rate of post-consumer waste from paper products guarantees large volumes of domestic recovered paper for the manufacturing of paper products. Nevertheless, according to the Confederation of European Paper Industries (CEPI) estimates, in addition to the paper industry use, over 8% of collected paper is used in other recovery applications, like construction material, animal beddings, compost and energy (COST, 2010). As said, recovered paper is mainly domestic, but a growing volume of imported recovered paper is happening, and currently is around 4.0 Mt (VDP, 2015). Further, paper still requires a volume of high quality pulp (primary raw material). In 2012, imported chemical pulp came mainly from Scandinavia (Sweden with 18%, Finland with 14%) or South America (Brazil with 28%, Chile with 7%) to a total of 3.5 Mt (FÖP and Ökopol, 2013). These volumes however have been relative constant in the last years as for example in 1990 the import of chemical pulp was of 3.2 Mt (FÖP and Ökopol, 2013). In total, Germany imports account nearly half (55%) of the required raw materials for the manufacturing of paper (Dispan, 2013b). Despite the strict control established since March 2013 through the EU Timber Trade Regulation in certifying legal sources of raw materials, illegal materials coming from cuttings in Russia, Indonesia or Brazil are entering the European Union (FÖP and Ökopol, 2013). The amount of this material finally used in Germany is very difficult to track as for example, printing material is not obliged to declare the origin of the paper. Although this phenomenon takes place, for the modeling purposes it must be ignored.

The use of recycled paper is gaining worldwide greater significance (Pickin et al., 2002) in order to reduce paper-related GHG emissions and as the use of wood for energy purposes is increasing (Mantau et al., 2010b). Germany has currently one of the highest recovery rates in the world with around 76% (VDP, 2012; VDP, 2015). Recycling technologies for paper are relative mature and no breakthrough is expected in the coming years as the current principles will be used in future deinking and recycling processes. Some improvements in the separation and selection steps might be achieved, as well as changes in paper additives (green chemicals, organic pigments, for instance). For paper products the recycling efficiencies not only depend on technological innovation, but on the quality of the recovered material which include additional substances besides pulp fiber. Recently, the incorporation of nanotechnology applications, functionalized fibers, and changes in printing technologies like water-based inks, digital printing or flexoprint may lead to a decrease of the deinking yield (Dispan, 2013b). Although, both positive and negative changes are expected, recycling rates will maintain at least at current levels.

The growing digitalization of information sets a challenge for the paper industry, especially the market for graphic where newspaper and other printing papers will be reduced in demand, while other paper groups like hygiene, cardboard will increase (Dispan, 2013b). Because of the increase of commodities manufacturing, packaging material has shown an increase of production volume (VDP, 2015). The paper industry will continue to grow, with the development of new applications. This industry is expanding its product portfolio with biorefinery plants and develops new basic materials (Mantau et al., 2010b). A tendency to reduce per capita consumption in the developed world is perceived. For example France, Finland, Sweden, USA and Canada, has shown reduction of per capita consumption since the last decade. The exception is Germany where the consumption has slightly increased (FÖP and Ökopol, 2013).

### 4.3.2. Wood industry

For the last decade, Sweden, Finland and Germany have been among the top timber producers and consumers in Europe. The largest is Sweden followed by Germany with a slight 2-3% lower volume. The German wood industry is composed of three main industries: the forestry industry, the wood-processing industry and the wood-furniture industry. In the forestry industry harvesting of standing biomass and logging to produce roundwood is taken place. In the wood-processing industry materials or products such as sawnwood (composed of softwood and hardwood), veneer, wood-based panels and boards are manufactured. In this industry by-products like sawmills residues are largely used for manufacturing of energy products, such as pellets, which are expected to have a larger market in the future (Mantau et al., 2010a). Sawnwood had in the last years the largest production volumes of semi-finished products with around 23 million $m^3$ in Germany (VDS, 2010), where around 12.2 million $m^3$ are destined for boards and panels, like particle chip boards or oriented strand boards among others (Mantau et al., 2012b). Finally, the main products from the furniture industry are directed to dwellings or non-residential buildings.

The wood industry is largely composed of small and medium businesses and some big industries that supply mostly wood panel products and sawmills (VDS, 2010). The wood industry relies on the permanent supply of wood coming from forests harvesting or secondary raw materials. In the last years, an increase in imported wood has been perceived, despite Germany's forest resources are the largest in Europe (ETTF, 2011). However, the possibilities of expansion are quite limited. Germany is becoming more dependent on wood imports, especially from European countries with an increase of almost 25% between 2007 and 2011 (ETTF, 2011; Schiller et al., 2015; Stuchtey and Below, 2015). In the case of manufacturing of paper, for instance, only 17% of the wood has domestic origin (FÖP and Ökopol, 2013) On the other side, the imports from countries outside the EU is decreasing falling by 9% between 2007 and 2011 (ETTF, 2011). This in part constrain the directives of the European Commission to use woods from sustainable harvested forests within the

European Union, leading to a total use of 90% of the European wood-processing industries to use European wood.

As seen in figure 20, between 1950 and 2013 the wood industry has developed largely. Consumption of wood has almost increased three-fold, from nearly 20 million m³ to 60 million m³, while both exports and imports have increased from 1 million m³ up to more than 35 million m³, mostly coming from imported flows (Dieter, 2002; Seintsch, 2011; Weimar, 2013). Since 2007 moderate increases, or even decreases have been identified within the wood consumption for material uses (Mantau, 2008). This slower rate of increase is expected to continue in part because of the financial crisis and also because the increasing demand on use of wood for energy purposes (FAO, 2009; Mantau et al., 2010b). Nowadays, the domestic wood demand varies around 70 to 75 million m³ and the total consumption circa 72.5 million m³ (Weimar, 2013). From these volumes, the material use corresponded to 46.9 million m³ and the rest for energy purposes. This means, that nearly 65% of the domestic wood had a material use. Energy uses are mainly domestic heating and co-generation power plants and account for one-third of the total resource use. Notwithstanding, a shifting trend with higher shares of wood for energy purposes is perceived. The production volumes showed a very sharp increase between 1990 and 2000 increasing from 28 million m³ to almost 60 million m³. Currently, an amelioration of the volumes is perceived, however production efficiencies are expected to increase. This effect has impacted the volumes of exported volumes hitting 40 million m³ at the beginning of the millennium, while imports have kept a rising trend reaching nearly 42 million m³.

A section of the wood industry is the panel industry, and it had for long time a small production volume. After 1990 the demand grows as new types of panels like medium density fiberboards, oriented fiber boards, among others are developed (Nimz et al., 2000).

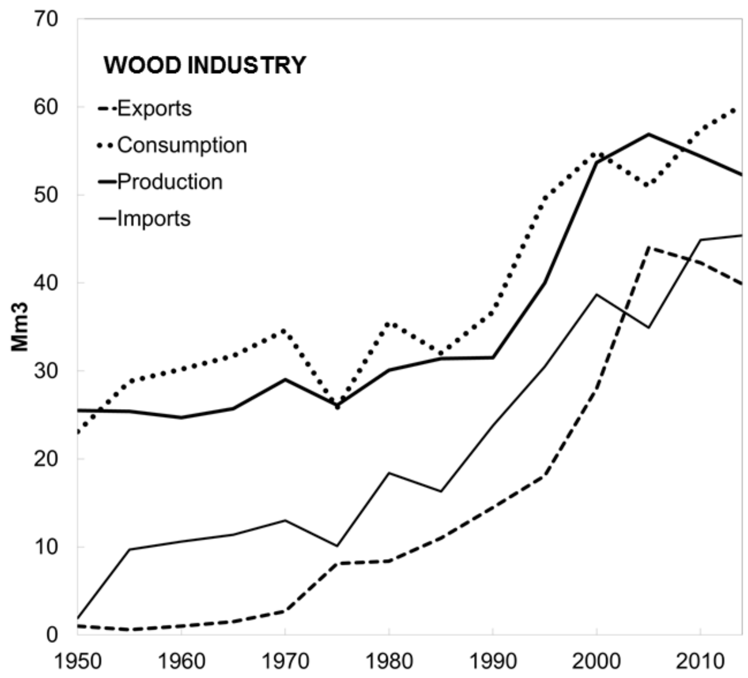


Figure 20: Development of the wood industry in Germany

In the material uses, wood is still largely use for construction of built environments, that is dwellings and non-residential buildings (Buchanan and Levine, 1999; Höglmeier et al., 2013;

Deilmann et al., 2014; Schiller et al., 2015), used in the manufacturing of commodities (Kohlmaier et al., 2007) and indoor areas of built environments. Wood is also used for packaging. Under this perspective, the wood industry provides services in residential and non-residential buildings, well-being and packaging within the AMS.

The wood industry is gaining new markets that are shifting the traditional demands. The use of raw materials for chemical products, textiles or the incorporation of short rotation coppice for energy uses, although still highly uncertain, are becoming more and more relevant. To date, few studies are available that explains the future for this type of woody biomass (Mantau et al., 2010a), however the increase in use for energy purposes such as power, heat or second generation fuels is seen within the European countries (FAOSTAT, 2015; Laurijssen et al., 2010). The possible future-near scarcity of fossil fuels will make wood a major substitute in the chemical industry and a greater demand for wood can be expected. This trend, however, can be relegated or at least develop with a slower dynamic, because of the low current price of oil, and this could trigger a decrease in energy wood consumption and promote the use of wood for material uses. Under this delicate and uncertain balance, the consumption of wood for the future is not clear. However, since energy efficiency targets must be met, a trend of increasing consumption might happen (Mantau et al., 2010a) and products like liquid biofuels or further renewable sources for energy supply can receive incentives.

At a global level, the energy demand in the world will increase at least 50% of current values by 2030 (VCI and Prognos AG, 2013), especially in developing countries. This might trigger an increase in the exported renewable resources and will lead to a decrease of material use from 55% to 43% by 2030 (VCI and Prognos AG, 2013). Even more, recent policies have fostered the use of wood as energy use and have had an effect of lower growth in material use. In this sense, cascading of sawmill by-products is seen as an interesting approach for coping resource scarcity (Höglmeier et al., 2013). Wood plastic components are being used in construction and transport with developing applications (Kamdem et al., 2004; Ashori, 2008) or the textile industry with the use of cellulose. Finally, under the growing consumer group with sustainability, wellness and recycling trends, wood products acquire an important role.

### Accountable units

As discussed in chapter 3, the EW-SFM is constructed on a material basis. This simplifies the modeling for the material system to a systematic approach based on material balances. The paper and plastic industries report data statistically in mass units and can be used straightforward. However, as seen above, the wood industry, on the contrary, report in volume units, where each of the semi-finished products, like plywood, veneer, particle board, fiber board, oriented strand boards, and so on, have specific density and humidity (Nimz et al., 2000; Dieter, 2002; Man- tau et al., 2005; UBA, 2007; Mantau, 2008; Mantau et al., 2010b). Since each type of product have different manufacturing process, not all products have same densities. This difference in accounting is resolved using an average density value for each semi-finished product to convert volume data in mass data.

Table 4 summarizes the average densities of the different wood products. Nevertheless, among the different European countries no consensus is found about manufacturing efficiency factors nor in the densities for the production of one cubic meter of sawnwood from roundwood. Therefore, since the model is concentrated in Germany, data from the German industries and institutes were favored. The conversion factors of wood in cubic meters to tons are defined on international basis (UNECE and FAO, 2010; Weimar, 2013; Weimar, 2015).

Table 4: Average wood products conversion factors (UNECE and FAO, 2010; Weimar, 2013; Weimar, 2015)

| Wood product | Mt | Mm3 | kg/m3 |
|---|---|---|---|
| Sawnwood | 990 | 1500 | 660 |
| Plywood | 600 | 750 | 800 |
| Medium/High density fibreboard | 780 | 1300 | 600 |
| Chip Particle Board | 650 | 1000 | 650 |
| Oriented Strand Board | 100 | 250 | 400 |
| Veneer | 2625 | 3500 | 750 |
| Other wood semi-finished products | 2635 | 3500 | 750 |
| Glue, Paints, Protection | 105 | 150 | 700 |

### 4.3.3. Plastic industry

Since the last decades, the German plastic industry has become one of the largest and leading of its kind worldwide (GTAI, 2015). Similarly the German economy has one of the highest plastic consumption volumes around the world (Patel et al., 1998; OECD, 2010b) with a per capita consumption of nearly 140 kg/cap per year (Consultic, 2013). It is the largest consumer in Europe, followed by the Italian and French markets. Additionally, the plastic industry covers a share between 7.5-8% of the global production (Dispan, 2013a) and nearly 6% of the domestic industrial production (GTAI, 2015). Figure 21 illustrates the development of the German plastic industry from 1950 to 2013. The industry has recorded very steep annual production and consumption increases (over 7%) since 1950, and has become a leading export nation. In the last years, however, because of the concurrent financial crises a cutback was suffered which has been rapidly recovered to previous production and consumption levels (Dispan, 2013a).

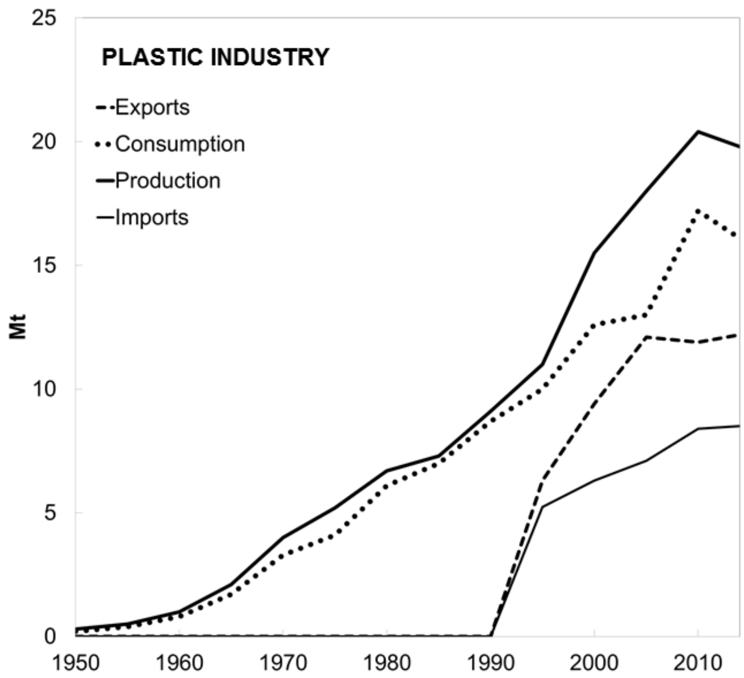


Figure 21: Development of the plastic industry in Germany

The German plastic industry is composed of two main branches: (1) the manufacturing of basic polymers and (2) the manufacturing of final engineered and high performance goods. The supply of raw materials of polymeric matrices or plastics comes from the oil+gas industry and its derivatives (Dehoust et al., 2006) and therefore influenced by the fluctuation of the oil price. It steps away from renewable sources prioritizing non-renewable ones as shown in figure 22.

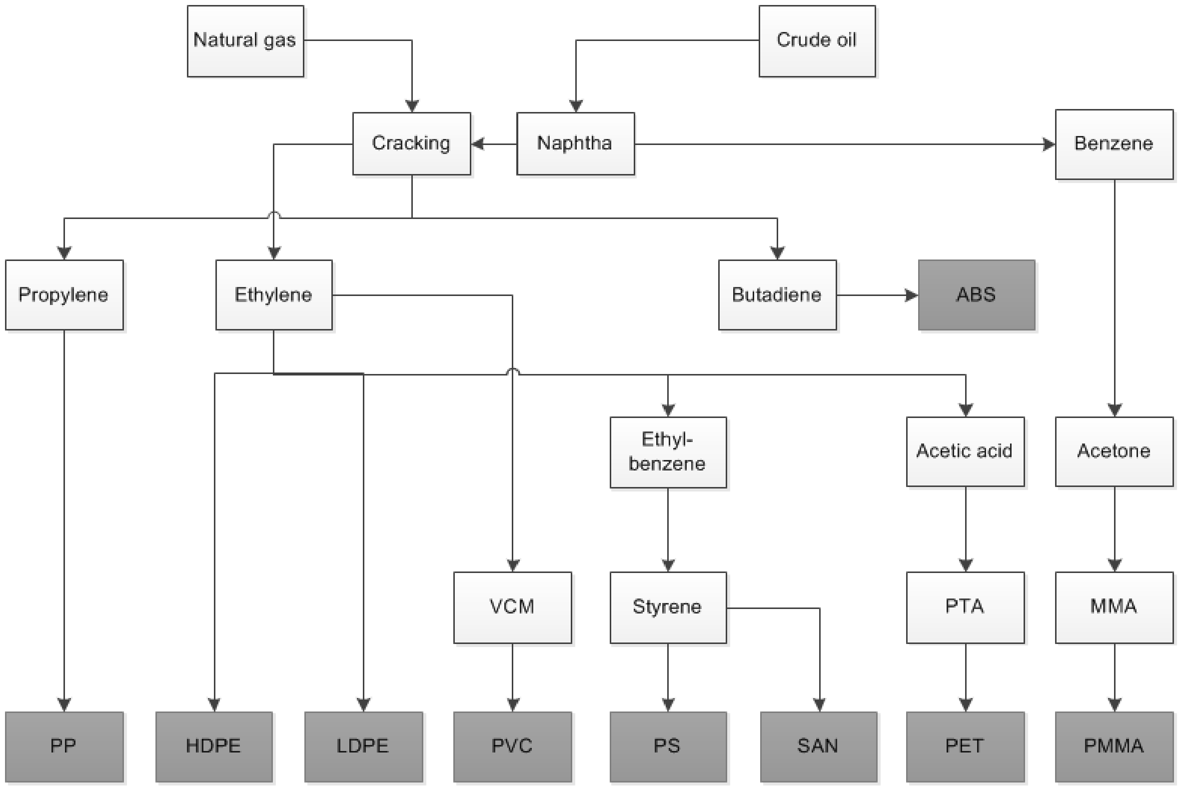


Figure 22: Polymerization processes from non-renewable sources, where dark gray boxes represent polymer matrices (Adapted from: Dehoust et al., 2006)

In 2013, the German plastic industry produced a total of 19.8 Mt of plastics resins and polymer matrices for processing (Consultic, 2013). Of these, 12.2 Mt were exported and in addition 8.5 Mt were imported. Thus, a volume of 16.10 Mt for the manufacturing of plastic goods was available in this same year. This volume is composed in a large percentage for consumer and capital goods, while nearly a quarter is destined to the manufacturing of complementary applications[4], like glues, paints, resins and fibers (Consultic, 2007; Consultic, 2009; Consultic, 2011; Consultic, 2013). Germany trades with the European Union (EU-28) reached nearly 72% of the whole export volumes (GTAI, 2015).

From the basic polymeric branch resins such as low-density polyethylene (LDPE), high-density polyethylene (HDPE), polystyrene and expanded polystyrene (PS/EPS), polyethylene-terephthalate (PET), polyurethane (PU), polypropylene (PP) and polyvinylchloride (PVC) are found. The engineering plastics and high performance polymers are nascent market niches, with a current small market share, low innovation indicators (Dispan, 2013a; Vassiliadis, 2014) and are classified as "other polymers" in the model. Figure

[4] These additional applications are not considered in the domestic demand of plastic final goods (and in the evaluation of the AMS) as these materials are normally destined to other industries like stone processing or the textile industry and therefore not traceable and dissipated along the production chain.

23 describes the standard and engineered polymer shares in terms of production and processing volumes for 2013 (VCI and Prognos AG, 2013) within the German economy.

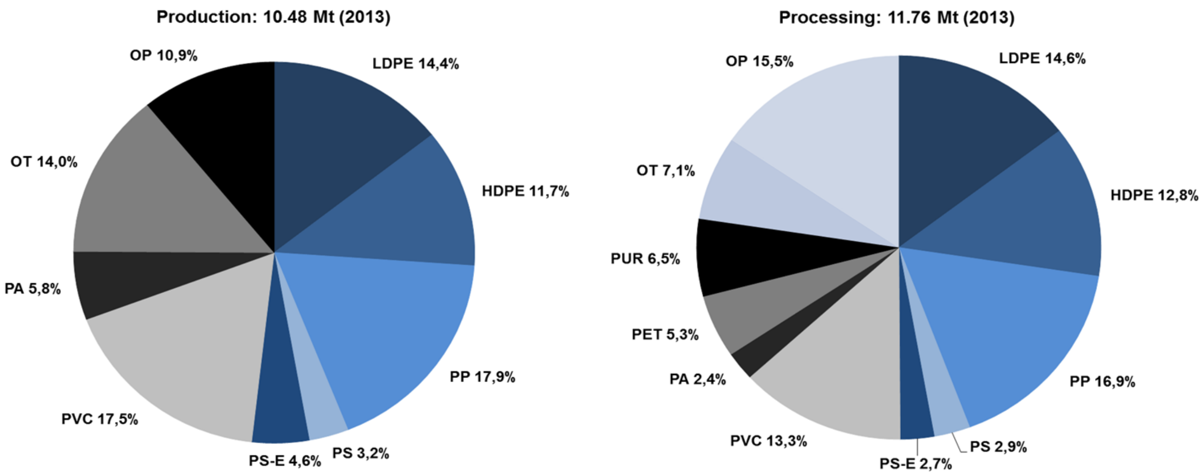


Figure 23: German production and processing volumes of the plastic industry in 2013. LDPE: Low-density polyethylene; HDPE: High-density polyethylene; PP: Polypropylene; PS: Polystyrene; EPS: Expanded Polystyrene; PVC: Polyvinyl-chloride; PA: Polyamide; PET: Polyethylene-terephthalate; PUR: Polyurethane; OT: Other thermoplastics; OP: Other polymers. (VCI and Prognos AG, 2013)

A third important and closely related industry is the "rubber industry" that processes and produces natural and synthetic rubber (STATISTA, 2015). Despite the differences between both industries its applications are widely extended in the anthroposphere, mainly in the transport sector and construction with the manufacturing of tires and production of elastomers. For the purpose of this work the plastic industry will include the rubber industry as part of it as well.

Table 5: Distribution of polymers in selected services in 2013 (Consultic 2013)

| Polymer | Total | Packaging | Construc-tion | Transport | Electronic | Other services |
|---|---|---|---|---|---|---|
| LDPE | 14.6% | 30.7% | 1.9% | 0.6% | 10.4% | 10.6% |
| HDPE | 12.8% | 21.3% | 14.3% | 8.6% | 2.2% | 3.9% |
| PP | 16.9% | 20.8% | 6.6% | 26.9% | 18.6% | 16.6% |
| PS | 2.9% | 2.9% | 2.5% | 0.0% | 7.4% | 3.6% |
| EPS | 2.7% | 0.9% | 10.0% | 0.0% | 0.0% | 0.0% |
| PVC | 13.7% | 4.7% | 41.4% | 3.7% | 3.0% | 5.3% |
| ABS, ASA, SAN | 0.3% | 9.76% | 0.6% | 8.2% | 13.4% | 3.0% |
| PMMA | 0.6% | 0.0% | 0.8% | 1.1% | 0.3% | 1.0% |
| PA | 2.4% | 0.6% | 0.9% | 8.5% | 11.3% | 1.9% |
| PET | 5.3% | 14.6% | 0.0% | 0.2% | 1.4% | 0.3% |
| PUR | 6.5% | 0.3% | 8.1% | 14.0% | 5.3% | 10.7% |
| OT | 3.9% | 0.2% | 1.8% | 14.4% | 17.0% | 3.7% |
| OP | 15.6% | 2.7% | 11.2% | 13.7% | 9.8% | 39.4% |
| Total | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |
| In million tons | 11.76 | 4.12 | 2.76 | 1.18 | 0.71 | 2.99 |

*Comments:* LDPE: Low-density polyethylene; HDPE: High-density polyethylene; PP: Polypropylene; PS: Polystyrene; EPS: Expanded Polystyrene; PVC: Polyvinyl-chloride; PA: Polyamide; PET: Polyethylenetherephtalat; PUR: Polyurethane; OT: Other thermoplastics; OP: Other polymers

From these industries a large number of applications in wide market segments are found. Plastics offer solutions to several needs in the AMS such as packing, communication, transport, well-being, constructions and infrastructure, among others. The volumes of each processed polymer or plastic varies according to the service provided. The distribution of polymeric raw materials for processing in terms of services is shown in table 5, where the largest share is used of packaging (35.0%) and construction (23.5%). In construction PVC is mostly used (Schiller et al., 2015) while LDPE is the most common plastic for packaging (Kozlowski, 2006). In the same way, PP and "other polymers" like ABS are the most used plastic in transport (Kozlowski, 2006) and electronic applications (Vyzinkarova and Brunner, 2013).

Figure 24 illustrates the use of processed plastics in terms of services. As an example, a detailed description of the service packaging indicates the type of plastics involved, where a number of end product shares are defined, like films (38.0%), bags (11.5%), containers (20.0%), bowls/cans (14.0%) and other goods (16.5%) (VCI and Prognos AG, 2013; GTAI, 2015). To fit the granularity and purpose of the economy-wide stock-flows analysis, this information was compiled into appropriated product groups as listed in table 6 in section 4.4.

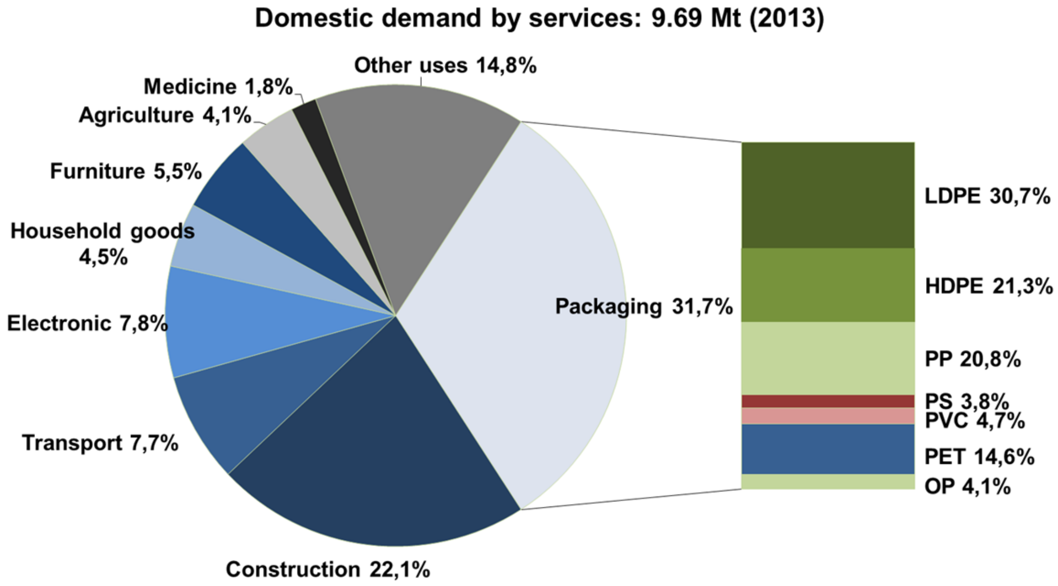


Figure 24: Service distribution of the plastic industry in 2013 and uses of plastics in packaging. LDPE: Low-density polyethylene; HDPE: High-density polyethylene; PP: Polypropylene; PS: Polystyrene (including PS-E); PVC: Polyvinyl-chloride; PET: Polyethylenetherephtalat; OP: Other polymers (PA, PUR, PMMA, ABS)

The basic polymer manufacturing had a strong manufacturing branch in Western Europe. However, because of the increase of demand of these polymers in developing countries, the manufacturing of these polymers have been affected in the developed world. Many plastic industries are moving to Asian or Chinese markets to initiate operations there (VCI and Prognos AG, 2013). This might leave the basic polymer industry in Germany in a critical situation. Thus, in the coming decades for the plastic industry seem very promising as expansion in new developing markets with growing demand, development of further applications (Vassiliadis, 2014) and the current low price of its main raw materials are positive factors for the industry. In the latter, besides a reduction in the cost of production and sale, cheaper raw materials might create concerns for the stability of recycled plastics. However, the low oil price is prone to increase in the coming years to 80 US dollars per barrel by 2020 (Smith, 2015) after reaching its lowest level since 1998. This of course favors the use of primary raw materials rather than secondary raw materials. However, the finite condition of the resource might trigger again the use of secondary raw materials. This factor will require political support in order to promote a continuous flow of secondary raw materials (Stuchtey and Below, 2015) independent of the strong debate on peak-oil and consumption of reserves (Worldwatch Institute, 2015).

Contrary to the critical situation of the wood and paper industry, which in the last decade it has struggled to maintain competitiveness in the international markets, the plastic industry shows no signs of deceleration or stagnation for the coming decades. In fact, the German plastic industry grows three times faster than the paper industry. The growing demand of basic polymers in developing countries has raised both the domestic and world production volumes. The effects in the domestic demand show a growth of nearly 4.1%. Under this conditions the German industrial capacity, because of raw materials supply and costs of production cannot compete (VCI and Prognos AG, 2013). Additionally, the plastic industry might face a slight decrease in the export volumes, cause by the production capacity of basic polymers in the country and by the growing production sites in developing regions such as Brazil or Asia. For this reason the markets of engineered polymers is gaining momentum in the developed countries. The export balance is slightly affected as the deliveries of basic polymers will continue. Therefore, domestic demand will need to be covered by imports and it is expected to increase 8 points up to 65% in 2030 (VCI and Prognos AG, 2013). Nevertheless, it is expected a total of 52% of the production to be exported.

The development of engineering polymers has a strong potential and a growth parallel with the manufacturing of plastics from renewable resources. Some studies estimate a replacement of fossil raw materials in coming years in the chemical industry up to 40% of current levels (VCI and Prognos AG, 2013). In the same perspective, more uses of plastics might displace in around 20 years glass and metal for polycarbonate in the automobile industry, showing significant substitution effects in the coming years. The use of plastics in automotive use as measures for increasing vehicle performance and reduction of fuel consumption is taking place (Kozlowski, 2006; Dispan, 2013a). Further, the innovation technologies between polymers and non-polymeric matrices have created polymer composites (Nieber, 2014). Such versatility opens new markets and offers technical advantages with new high-tech functions using carbon, polymer or wood-plastic composites (Ashori, 2008; Cote et al., 2009), in nanotechnology (Möller et al., 2013), organic photovoltaics (Sekine et al., 2014), lightweight materials (Nieber, 2014), among others. Engineering polymers exports should grow around 2.7% annually until 2030 and have an effect in its domestic demand (2.3%) and production (2.5%).

The chemical stability of plastics gives on one side durable, resistant and cheap materials used as seen above for the satisfaction of multiple societal needs. Notwithstanding, these advantageous characteristics are creating an environmental burden, caused by the permanent flow of plastic wastes into the biogenic system.

## 4.4. Industrial carbon-based product groups

The material and energy use of carbon-based materials at the anthropogenic level coming from three carbon-based industries was discussed above. Considering figure 16, at least a total of eight to nine thousand products for the satisfaction of several services are available in the market. These final goods are, however classified for modeling purposes in an adequate number of product groups, based on the provided service, material and use as described in section 3.2.1. For instance, data for raw material composition (Pingoud, 2003; Hischier, 2007; Consultic, 2013), manufacturing efficiency (Hashimoto et al., 2004; Mantau et al., 2010a; COST, 2010), in-use lifetime (Murakami et al., 2010; Oguchi et al., 2010; Aktas, 2011; Höglmeier et al., 2013) and annual market share (VDP, 2015; Mantau et al., 2012a; Consultic, 2013) among others are assigned. In some cases personal communications (Uihlein, 2013) complemented the information and in missing data assumed values were considered.

### 4.4.1. Wood-based products

Wood-based products correspond to both final wood and paper products. The use of wood has a long tradition in the German anthroposphere: from heating and construction materials to the recently new energy technologies such as biomass-to-liquid (BtL) or polymerization of biopolymers and biofuels with fast pyrolysis processes. In terms of material uses, wood supplies services in packaging, communication, built environments and infrastructure and well-being, mostly concentrated in the construction sector. Examples of products goods for housing are components for doors, windows, floors, load-bearing structures, for packaging pallets and boxes, among others. In communication just paper products are found. In the same perspective, wood is also used for heating/power purposes with final wood products for energy uses, like pellets, wood logs or BtL products. Finally, products for well-being, as a service that bring comfort and increases life quality are hygiene paper, furniture, other wood and paper products like toys, instruments and so on.

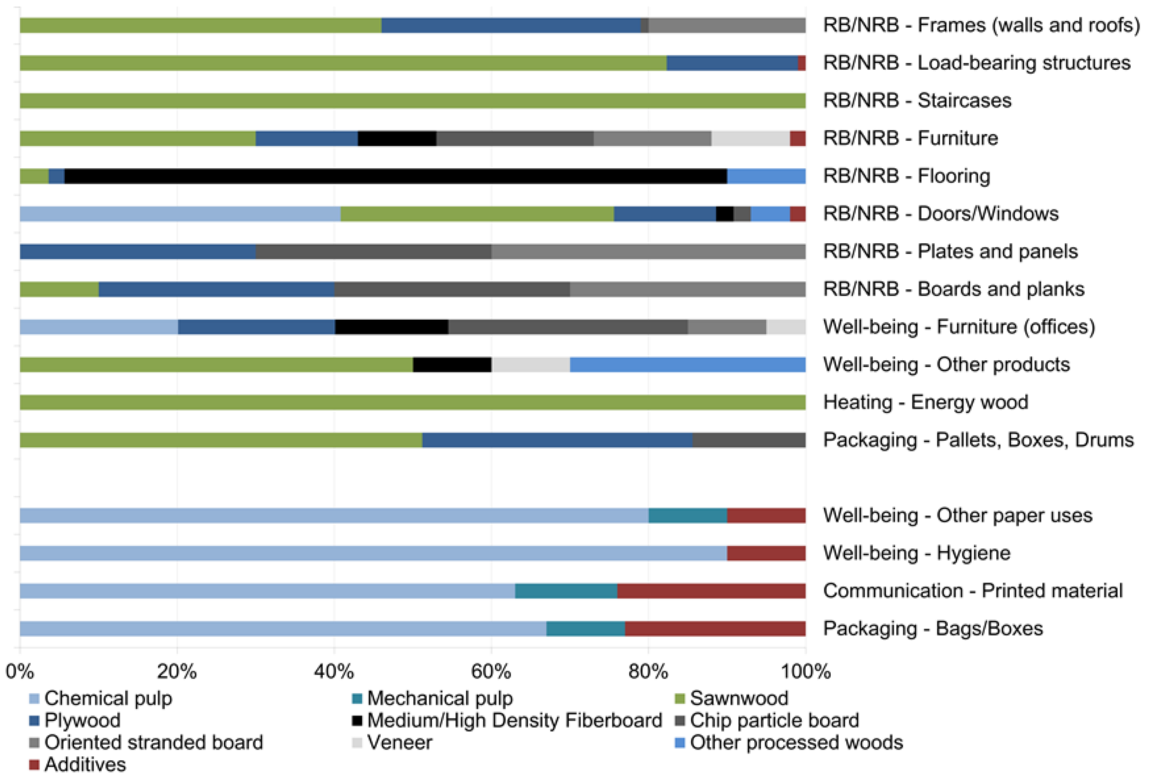


Figure 25: Production function values of wood-based products. RB/NRB: Residential/Non-residential building

The product groups for the paper industry are mainly three, corresponding to types of paper services: packaging, communication and well-being. The latter is divided in hygiene and other paper uses. For the granularity of the model, these four groups cover most of the expected services the paper industry can deliver. Based on information from nearly 70 pulp and paper industries in Germany and using available statistical and manufacturing data (Virtanen et al., 1993; Hekkert et al., 2000; VDP, 2009; VDP, 2012; VDP, 2013a), an adequate and descriptive list of the main pulp and paper products within the defined services was created.

Product groups apart of providing determined services are constituted or manufactured with specific types and amounts of raw materials. For the analysis of the material system in the anthroposphere, the knowledge of the material composition has important effects on the current and future demand of primary and secondary raw materials, as well as the composition of post-consumer wastes.  In figure 25 the average raw material composition of each wood-based product group is presented. The complete values of the raw material composition per product groups are found in table A.9 in Annex A. Paper products have a high use of chemical pulp, while sawnwood is the main raw material for wood products. In the paper products the use of additives is relative high in comparison with wood products. Fillings and finishing of papers are used for different applications (Blechschmidt et al., 2000; Tillmann, 2000).

### 4.4.2. Plastic products

Plastic products cover partially similar services as wood-based products, but it also has stronger influence in services like transportation with plastic components for vehicles, infrastructure where canalization of potable water and sewages, for example, or the electricity sector which has insignificant wood components. The packaging of liquids or medical substances is reserved for plastic products (besides the traditional use of glass). The diversity of plastics and the multiple plastic products provide a challenging task for expressing the largest product pallet in terms of services and raw materials. Notwithstanding, an average composition of raw materials for plastic product goods for the selected services is illustrated in figure 26. These values are also found in table A.9 in Annex A. Practically every service group requires a fraction of every polymeric raw material. Despite the interest of modeling standard polymers like low-density polyethylene (LDPE) or polyvinylchloride (PVC) which are widely use in anthropogenic activities (Dehoust et al., 2006; Consultic, 2011) the diversity of engineered plastics for specific applications in services like transport, communication and well-being adds up a large volume of small quantities different types of plastics (Consultic, 2013; Martens, 2011e). In this group more specialized polymers like Acrylonitrile Butadiene Styrene (ABS), synthetic Polyamides (PA), Poly(methyl-methacrylate) (PMMA) are present. As expected, the category "Other Polymers" has a very high fraction within the product groups. All these thermoplastics are in general light weight and can be injection molded and extruded useful for the manufacturing of a wide variety of products (Martens, 2011c). Because of the purpose of the model, and the reduced information available to these applications this general polymer group was defined as such.

### 4.4.3. Product groups

With the gathered information, a final classification of carbon-based products and goods from the carbon-based intensive industries for the model requirements can be built. Products and final goods provide a service during its in-use lifetime that ranges from years to decades.

Due to the product characteristics and type of use their expected operating time is limited as discussed in section 3.3.4.

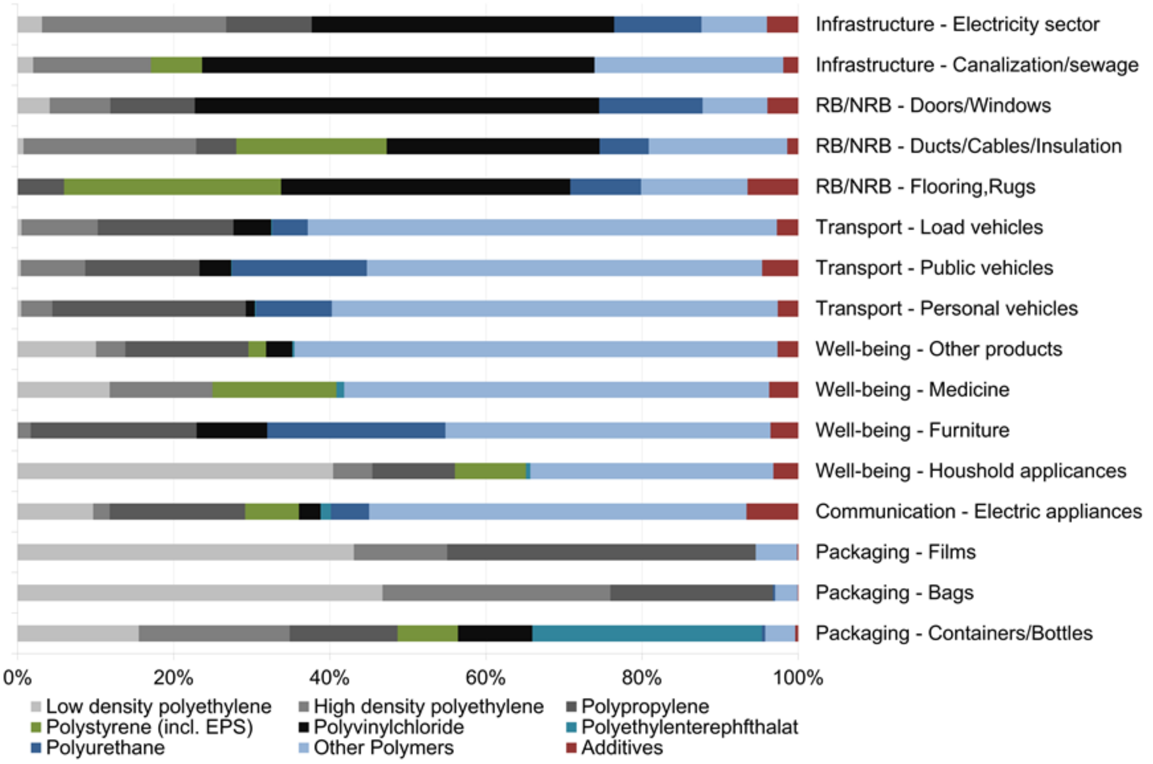


Figure 26: Production function values of plastic products. RB/NRB: Residential/Non-residential buildings

Table 6 is a fundamental data source for the model as it summarizes the complete palette of product groups for consumption, including information from the service it provides, and information about its in-use lifetime. Because of the large amount of carbon-based goods and manufactured products in the market, products were aggregated into representative product groups. In this context, a total of 30 product groups are distributed along eight services (that is packaging, well-being, heating, communication, transportation, non-residential buildings, residential buildings and infrastructure) where most of current pulp and paper, wood and plastic manufactured products are represented. As illustrated in figure 4, some of the product groups are present in various material groups as some services can be provided by several materials. For example, furniture or windows which can be made of wood or plastic materials. Therefore, a total of 44 product groups are listed and classified in four in-use lifetime groups, namely short (ST), middle (MD), long (LG) and very long (VL) in-use lifetime groups. Similarly, the same service can be present in various in-use categories. Thus, finally the 44 product groups are distributed in fifteen different services, as one service can be fulfilled by several materials.

Table 6: Service, product group and in-use lifetime classification of carbon-based goods

| Service | Product group | Min, yr. | Mean, yr. | Max, yr. |
|---|---|---|---|---|
| Short lifetime (ST) | | | | |
| Packaging | Paper - Bags/Boxes | 1.0 | 1.5 | 2.0 |
| | Wood - Pallets/Boxes/Drums | 2.0 | 3.0 | 5.0 |
| | Plastic - Containers/Bottles | 1.0 | 1.5 | 2.0 |
| | Plastic - Bags | 1.0 | 1.5 | 1.0 |
| | Plastic - Films | 1.0 | 2.0 | 3.0 |
| Well being | Paper - Hygiene | 1.0 | 1.5 | 2.0 |
| | Paper - Other paper uses | 1.5 | 3.0 | 5.0 |
| | Plastic - Household appliancesa | 1.0 | 3.0 | 5.0 |
| Heat and electricity | Wood - Energy-/ Fuelwood | 0.1 | 0.2 | 0.3 |
| Communication | Paper - Printed material | 1.5 | 5.0 | 15.0 |
| Middle lifetime (MD) | | | | |
| Non-residential buildings | Wood - Flooring | 7.1 | 15.7 | 24.3 |
| | Plastic - Flooring/Rugs | 7.1 | 15.7 | 24.3 |
| | Wood - Boards/Planks | 8.3 | 18.3 | 28.3 |
| | Wood - Plates/Panels | 8.3 | 18.3 | 28.3 |
| Transportation | Plastic - Personal vehiclesb | 6.0 | 15.0 | 18.0 |
| | Plastic - Public vehiclesc | 6.0 | 15.0 | 18.0 |
| | Plastic - Load vehiclesd | 6.0 | 15.0 | 18.0 |
| Well being | Wood - Other productse | 4.0 | 9.0 | 15.0 |
| | Plastic - Medical applications | 3.0 | 7.0 | 12.0 |
| | Plastic - Other productsf | 1.0 | 6.0 | 10.0 |
| Communication | Plastic - Electric appliancesg | 5.0 | 7.0 | 15.0 |
| Long lifespan (LG) | | | | |
| Residential buildings | Wood - Boards/Planks | 14.0 | 40.7 | 70.0 |
| | Wood - Plates/Panels | 14.0 | 40.7 | 70.0 |
| | Wood - Doors/Windows | 14.0 | 40.7 | 70.0 |
| | Wood - Flooring/Rugs | 14.0 | 40.7 | 70.0 |
| | Plastic - Flooring/Rugs | 14.0 | 40.7 | 70.0 |
| | Plastic - Doors/Windows | 12.5 | 27.5 | 42.5 |
| | Plastic - Ducts/Cables/ Insulation | 16.7 | 36.7 | 56.7 |
| Well being | Wood - Furniture (residential) | 14.0 | 40.7 | 70.0 |
| | Plastic - Furniture (residential) | 14.0 | 40.7 | 70.0 |
| | Wood - Furniture (non-residential) | 12.5 | 27.5 | 42.5 |
| | Plastic - Furniture (non-residential) | 12.5 | 27.5 | 42.5 |
| Non-residential buildings | Wood - Doors/Windows | 14.0 | 40.7 | 70.0 |
| | Plastic - Doors/Windows | 12.5 | 27.5 | 42.5 |
| | Plastic - Ducts/Cables/ Insulation | 16.7 | 36.7 | 56.7 |
| Infrastructure | Wood - Transport sector | 20.0 | 30.0 | 40.0 |
| | Plastic - Canalization/Sewage | 30.0 | 60.0 | 75.0 |
| | Plastic - Electricity sector | 20.0 | 40.0 | 60.0 |
| Very long lifespan (VL) | | | | |
| Residential buildings | Wood - Staircases | 21.0 | 61.0 | 105.0 |
| | Wood - Load-bearing structures | 21.0 | 61.0 | 105.0 |
| | Wood - Framesh | 21.0 | 61.0 | 105.0 |
| Non-residential buildings | Wood - Staircases | 25.0 | 55.0 | 85.0 |
| | Wood - Load-bearing structures | 25.0 | 55.0 | 85.0 |

Table 6 (continuation): Service, product group and in-use lifetime classification of carbon-based goods

| Service | Product group | Min, yr. | Mean, yr. | Max, yr. |
|---|---|---|---|---|
| | Wood - Framesh | 25.0 | 55.0 | 85.0 |

*Comments:* a) Kitchen/Bathroom/Non-electric devices; b) Parts in Cars/SUV/Motorbikes; c) Parts in Buses/Trains; d) Parts in Trucks; e) Toys/Instruments/and so on; f) Textiles/Toys/Instruments, and so on; g) PCs/TVs/Telephones; h) Walls/Roofs

Paper products are located in the short and middle in-use lifetime groups, while plastics and wood are distributed along the four groups. As shown in figure 27, the weighted average in-use lifetime (expressed in the different color intensities) from the three material groups range between 2.8 years to 46.9 years. Maximum in-use lifetimes reach 105 years for some wood products and minimums one year for some paper products. Wood products have in average the longest in-use lifetimes, followed by the plastic products and finalizing with paper products with in-use lifetimes of maximum five years.

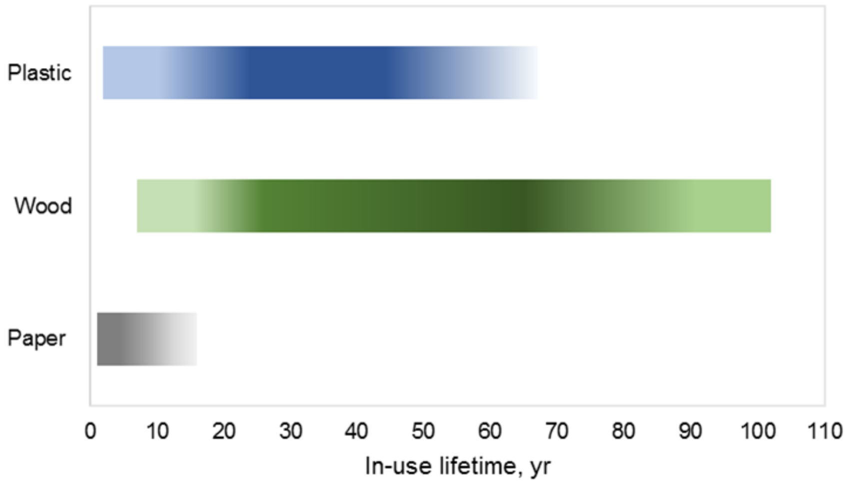


Figure 27: Weighted in-use lifetime average of carbon-based material groups

A second important aspect for the classification of final products and goods is the estimated market share of each material group that is paper, wood and plastic. As a result of the manufactured products heterogeneity and specific market development, the market shares of the three carbon-based material groups are independent. Market share values for the modeling periods are estimated with the calculated per capita consumption of services for each material and market data (Schiller et al., 2015; STATISTA, 2015; Deilmann et al., 2014; KBA, 2014). The market share defines the distributed annual amounts of goods in the domestic market expressed in terms of mass within its corresponding material groups. In table A.7 in Annex A, the current and estimated future market share of the material groups in terms of services are presented and used in the modeling process.

## 4.5. Post-industrial and post-consumer wastes classification

As discussed in chapter 3, within the AMS two main classification types of wastes are found. The first, are wastes coming from the manufacturing sector (post-industrial wastes) and the second waste originated by consumers (post-consumer wastes). Post-industrial wastes are mainly loss volumes of unprocessed raw materials or by-products from the manufacturing processes.

These include, mentioning some, wooding residues and dust, black liquor, polymer pellets or material cuttings. Most of the post-industrial wastes are assumed to contain very similar physical-chemical properties of the pristine or secondary raw materials used in the manufacturing sector. Thus, they are directly combined with the secondary raw materials at the product manufacturing sector. Furthermore, by-products such as green or black liquor from the paper industry are used for energy purposes (Hashimoto et al., 2004; Monte et al., 2009).

Post-consumer wastes are discarded or obsolete final goods after having completed its in-use lifetime within a consumption cycle. The packaging of new goods is also included. These types of wastes are used both for material and energy purposes. The variety, materials and chemical characteristics of the discarded products makes necessary a post-consumer waste classification to provide a structured and organized distribution, trade and utilization of wastes. Nevertheless, several European countries have developed own internal and historical system which difficult cross border trade.

For carbon-based materials several classification frameworks are found. The European grading scale for recovered paper EN 643 (European Standard Grades of Recovered Paper and Board) established in 2001 (revised in 2013) classifies paper in five main paper and board groups for recycling (CEPI, 2013). Therefore, the introduction of this norm provides a general guideline for the classification system for recovered paper. The classification of paper wastes is focused on trading grades of recyclable paper with little consideration in qualitative properties. In the update the classification system was reduced from five categories to four merging group IV (Kraft grades) into group V. Because of the high heterogeneity in each group, we mention main paper grades in each group. At the quality level, the revised version of the paper normative includes a quality criterion: the rejection of paper materials over a 1.5%-threshold of non-paper components in paper.

Similarly, the German government established in 2003 (revised in 2012) the ordinance on the management of waste wood, and classifies wood wastes in four groups based on type of use and level of contamination (AltholzV, 2012; Mantau, 2012b). The latter ordinance originates as in some wood-based materials, important quantities of non-wood products like varnishes, paints, preservatives among others (Nimz et al., 2000) are used and are not suitable, for instance, for recycling. On the other side, the wood classification includes qualitative criteria such as the contamination level of the recovered materials, caused by manipulation of materials at pre-consumption and also post-consumption stages, for example, the use of chemical preservatives in infrastructures (COST, 2010; CEPI, 2013).

Plastics are only mentioned in the Closed Cycle Management and Waste Act (or *Kreislaufwirtschaftsgesetz* (KrWG) in German), where it stipulates that beginning 2015, all plastic waste should be collected separately and at least 65% w/w of the municipal waste must be recycled by 2020 (Peek, 2004). A general classification for post- consumer carbon-based waste is summarized in table 7. Paper products are mostly destined for material use (classes I to IV). For wood products material use (classes I and II) and energy use (classes III and IV) are found. In the case of plastics on average a higher share (nearly 67%) is used for energy purposes and only 33% has material utilization, but no classification was found. Therefore, it is assumed a plastic post-consumer waste classification for both material and energy uses. The classification of post-consumer and post-industrial wastes, provide a qualitative guide for the allocation and use of waste in the different waste treatment processes.

Table 7: Suggested industry post-consumer waste classification of paper, wood and plastics

| Class | Paper (EN 643) | Wood | Plastic |
|---|---|---|---|
| I | 70-80% corrugated paper and board for deinking, magazines, newspapers | Waste wood in its natural state or only mechanically worked | Non-contaminated basic polymers |
| II | Unsold newspaper, paper not for deinking or colored | Painted or lacquered waste wood with no HOC or preservatives | Contaminated basic polymers |
| III | White woodfree paper | Waste wood with HOC and no preservatives | Mixed polymer matrices |
| IV | Mixed and kraft papers | Waste wood treated with wood preservatives or with PCBs content higher than 50mg/kg | Mixed and contaminated polymer matrices |

*Comments:* HOC: Halogenated organic compounds; PCB: Polychlorinated biphenyl; Source: (CEPI, 2013; AltholzV, 2003); n.a.: not available

# 5. Possible futures of carbon-based AMS in Germany

„Lassen Sie uns alles daransetzen, dass wir der nächsten Generation, den Kindern von heute, eine Welt hinterlassen, die ihnen nicht nur den nötigen Lebensraum bietet, sondern auch die Umwelt, die das Leben erlaubt und lebenswert macht."

**Richard von Weizsäcker, German President (1920 – 2015)**

In the past chapters the German context of the carbon-based AMS has been described, including the main carbon-intensive material industries and major sociotechnical and environmental current and coming trends. The industries are the paper industry, the wood industry and the plastic industry. Additionally, a thorough classification of the manufactured goods in product groups has been done. This classification included services, in-use lifetime and market share of these groups in the anthroposphere. The carbon-based AMS shows a dynamic and challenging future which was evaluated with a scenario approach. The results of the prospective analysis of the system between 2015 and 2055 will now be presented.

## 5.1. Scenario analysis

A scenario analysis adds a significant contribution in knowledge and orientation to the understanding of the possible future dynamic and behavior of systems and leads to the identification of opportunities, bottlenecks or potential challenges within them (Roehrl, 2012). The scenario approach aims to describe under an economy-wide perspective a likely and detailed development of anthropogenic carbon flows and stocks from the carbon-based industries within the defined system boundaries. From these analyses, relevant and valuable information can be withdrawn about consistent and possible developments of raw materials demand, stock building, waste composition and volumes, among other important system variables of the AMS. Further, it provides a perspective about the variability of the system from potential changes happening in the coming decades. The scenario analysis gives an adequate picture of the relationships and effects of anthropogenic carbon flows and stocks on the environment, society and economy in the coming years at a regional level. With a scenario approach, consequences about specific measures or changes in the material system within the perspective of circularity, all in the context of a globalized economy and trade, can be identified. Thus, the scenarios enable the opportunity of setting the national AMS inside a global perspective to understand the inter- and intra-systemic relationships.

## 5.2. Baseline and alternative scenarios

With the technical and statistical information from the carbon-intensive material industries found in chapter 4, in addition to the described modeling framework in chapter 3, an expected development and dynamics of an economy-wide carbon-based material system in Germany can be evaluated. For this a scenario approach is performed with a baseline scenario and seven alternative scenarios in order to obtain information for efficient management of carbon-based resources, wastes and emissions and a view of different potentials of circularity within AMS. Based on the current state of the German material system the baseline scenario presumes the most likely AMS development and growth counting on historic information. The alternative scenarios are proposed, where multiple and plausible changes are evaluated seeking new outcomes and responses of the output variables within the AMS.

The baseline scenario has two functions: first, it describes the past of the AMS using historic time-series and statistical data from 1929 to 2014 and second, it provides, based on current trends and expert opinions, the most likely future and probable development of the AMS until 2055. The historic part of the baseline scenario gives a complete yearly description of the AMS compensating for the information gaps of past model inputs and outputs. Historical values are modeled with logistic regressions based on the available time-series to estimate inputs values for every single year between 1929 and 2014. It enables a complete modeling process, as the model is constructed on an annual basis. These results also reinforces the reliability of the model in estimating past states of the AMS. The second function of the baseline scenario is the definition of the most likely future development of the material flows and stocks of the evaluated carbon-based industries, considering economic, political, social and environmental domestic and foreign affairs from 2015 to 2055. Figure 28 exemplifies time-series estimation with logistic regressions of plastic and paper per capita consumption in Germany. The same logistic estimations are done with every relevant input variable in the model when needed. As expected, some differences between the regression values and the historical values can be found, but the continuity of the historic development of the input variables is obtained.

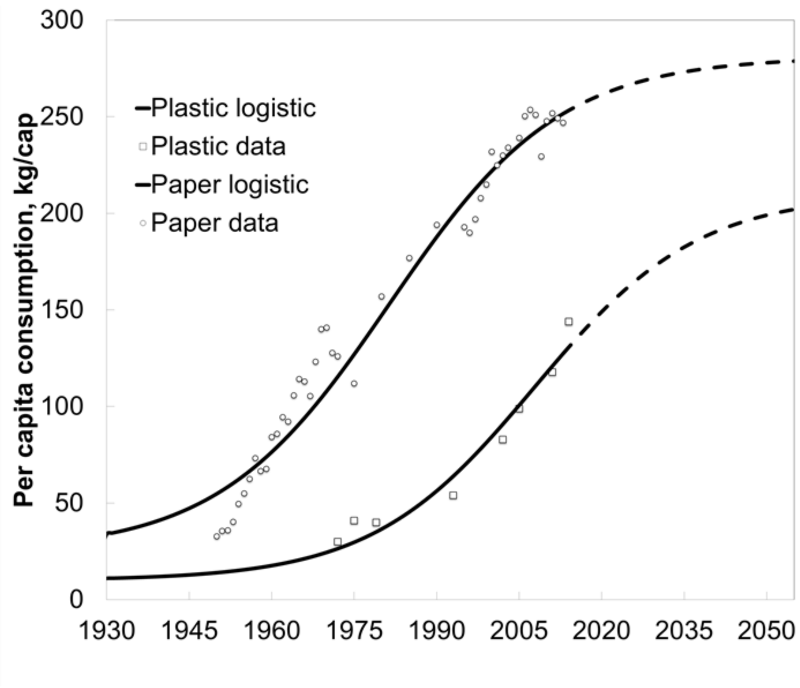


Figure 28: Statistical and estimated per capita consumption of paper and plastic products in Germany

The seven goal-oriented alternative scenarios evaluate possible and sound changes in variables and parameters with potentiality of occurrence in the future, and procures the intention of (1) identify possible ranges of the output variables, (2) the plausibility of potential changes according to available infrastructure, technology, policies and consumer behavior, and most important (3) describing systemic behavior to set strategies for achieving a better circularity within the AMS. The multiple futures are forged with the variation of internal and external inputs such as: per capita consumption, consumer choices of products, substitution of materials, use and demand of commodities (changes in the market share), waste treatment preferences, foreign trade, demographic dynamics, new consumption patterns, annual industrial growth, and technology innovations, among others. Because of the pure material approach, economic factors such as Gross Domestic Product (GDP) or Purchasing Power Parity (PPP) are not considered directly in this scenario analysis. The systematic variation and evaluation of the model parameters within the different scenarios, illustrates on the one side the effects of national and global trends at social, economic and environmental level and on the other side it generates a complete evaluation of the future behavior of carbon-based flows and stocks in the anthroposphere under the perspective of circularity.

The alternative scenarios model the period between 2015 and 2055, where year 2014 is the linking point between the descriptive modeling (modeling of past state of the AMS with statistical time-series) and prospective modeling (modeling of possible futures of the AMS), and combines both logistic and linear data regressions. These scenarios focus on specific changes *ceteris paribus* to evaluate probable outcomes and changes within the AMS. The change to linear regressions in the alternative scenarios for the estimation of future AMS states is done to avoid "multiple" pasts. The different settings and parameters in the final modeling year of the alternative scenarios affect the behavior of the logistic regressions, as it is one continuous curve from 1929 to 2055. Therefore, based on the baseline scenario results, constant initial conditions are given in every scenario. This means the information, setting and results from the baseline scenario from 1929 through 2014 are constant and define the starting values for the scenario analysis in 2015. This multi-regression approach provides flexible possibilities to investigate new developments and directions, without affecting the starting values in 2014.

To obtain a complete view and perspective of the AMS, the demand and distribution of primary and secondary raw materials, production, consumption and foreign trade of final goods, stocks dynamics of material and services, post-consumer waste flows and associated carbon emissions are evaluated for each scenario. Because the scenarios are focused on the period 2015 to 2055, the results of the baseline scenario are presented from 1950 on, to provide an idea of the past and future development, but focusing the attention on the future AMS development. For the alternative scenarios, results are presented from 2014 on. The first part will focus on the baseline scenario where the above-mentioned variables are thoroughly described. Secondly, in sections 5.5 and 5.6 the alternative scenarios are presented with its corresponding results.

## 5.3. The German carbon-based AMS according to the baseline scenario

Considering the industrial context described in chapter 4, Germany will surely continue to play a significant role in the world economy, in technology development, manufacturing and export, while maintaining domestic high life quality standards. The baseline scenario is a business-as-usual scenario. It takes the current state of the German material system and simulates the most likely developments in all the model variables based partially on historic information and on scenario reports from the carbon-based material German industries (Trauth and Schönheit, 2005; VCI and Prognos AG, 2013; Mantau et al., 2010a; Weimar, 2013; FÖP and Ökopol, 2013; Consultic, 2013; VDP, 2015). In general, Germany will enjoy continuous economic growth, though probably with a slower dynamic as in past years, showing still signs of a healthy development of the socioeconomic metabolism. Notwithstanding, a shrinking population phenomenon will most likely take place. As described in figure 17, the German population will have a cutback from 82 million in 2014 to nearly 68 to 70 million in 2055 (DESTATIS, 2015b). This is a critical cause for the whole German AMS as it implicates unknown and counteracting effects on the economic growth strategy.

Within the carbon-based material industries, the plastic industry production is expected to have a three-fold faster growth than the paper industry. For the next fifteen years this latter industry will have an expected annual stable growth rate of around 0.5-0.7% (Dispan, 2013b; FÖP and Ökopol, 2013), while the plastic industry between 1.5-1.8% (Dispan, 2013a; VCI and Prognos AG, 2013). This strong growth in the plastic industry compared to the paper and wood industry is expected caused mainly by the increasing demand of the developing countries. The wood industry shows annual growth rates between 1.3-1.6% (VCI and Prognos AG, 2013; Mantau, 2012a). Assuming a long lasting German export policy and saturation in the consumption of some carbon-based consumer and capital goods, as shown in figures 18, 20 and 21 in section 4.3, it is assumed lower domestic consumption growth rates than the production values. In this sense the annual per capita consumption of carbon-based products for the baseline scenario are: 0.3% for the paper products attaining 279.1 kg/cap in 2055, 0.5% for the wood products for a per capita consumption of 532.6 kg/cap (including energy use) and 0.9% for plastic products representing 203.1 kg/cap in 2055.

On the other side, due to the huge discrepancies regarding total consumption volumes between Germany and China, Brazil or India, a catching up of developing countries is assumed with higher growth rates. Total consumption volumes of carbon-based materials are increasing globally, with some varying dynamics in the per capita consumption. Here, the annual growth rate for foreign per capita consumption of paper is 1.3% (or 91.7 kg/cap) and for plastics is 2.1% (109.2 kg/cap). For the wood material group, within the literature, the foreign per capita consumption has divergent values. An estimate based on the statistical office of the Food and Agriculture Organization (FAOSTAT) sets for 1990 a foreign per

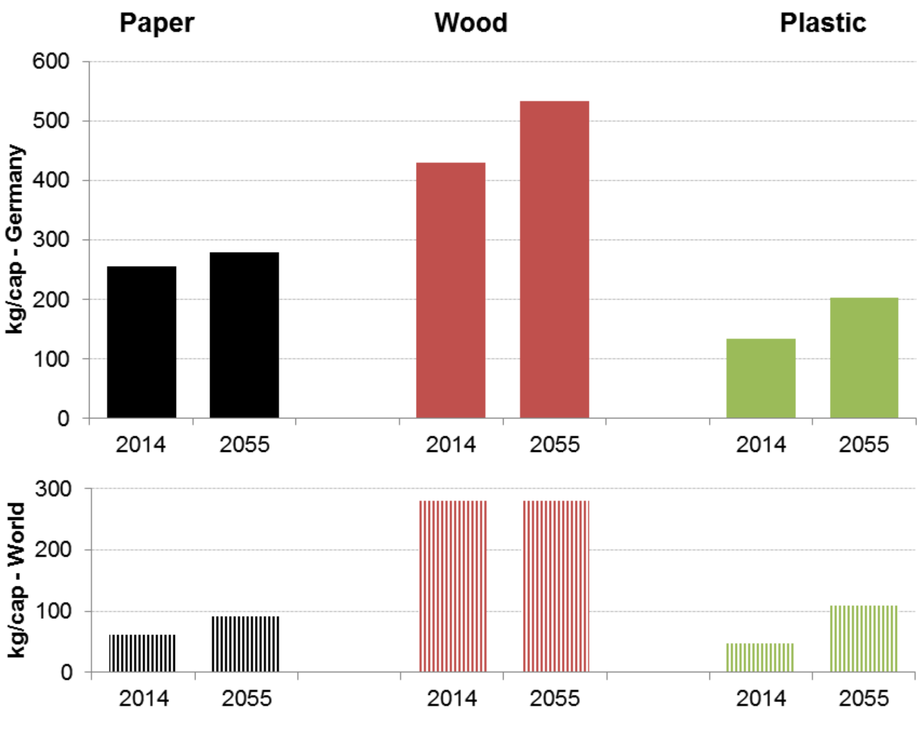


Figure 29: Estimated per capita consumption of paper, wood and plastic goods in 2014 and 2055 for Germany and worldwide

capita consumption of nearly 415 kg/cap (FAOSTAT, 2015); for the same year FAO (2009) reports 193 kg/cap (both excluding energy use). Similarly, for the year 2005 with FAOSTAT (2013) a consumption of 315 kg wood/cap is estimated, while the second source reports 154 kg/cap (FAO, 2009), both just for material uses. This discrepancy is systematic along both time series data, which provides a general perception that in reality the foreign per capita consumption of wood is decreasing globally, despite the increase in the total global consumption volume of wood. For the modeling purposes a middle value was chosen, where no growth is considered maintaining current levels (280.1 kg/cap - excluding energy use). The current and final per capita consumption values for Germany and the rest of the world for the baseline scenario are summarized in figure 29. The complete per capita consumption regression values and data information are found in figure A.1 and table A.1, respectively in Annex A. A summary of the description of the baseline and alternative scenarios with its main assumptions is found in table 9 (see page 100) where all scenarios are compared.

Further, technology-related parameters have to be defined. The manufacturing efficiencies are set in a range between 0.82 (for paper) and 0.93 (for wood) as presented in table A.3 in Annex A. The standard in-use lifetime of products goods for each product group range from short in-use lifetimes (< 1 yr.) to very long life-times (> 100 yrs.) as shown in table 6 in section 4.4.

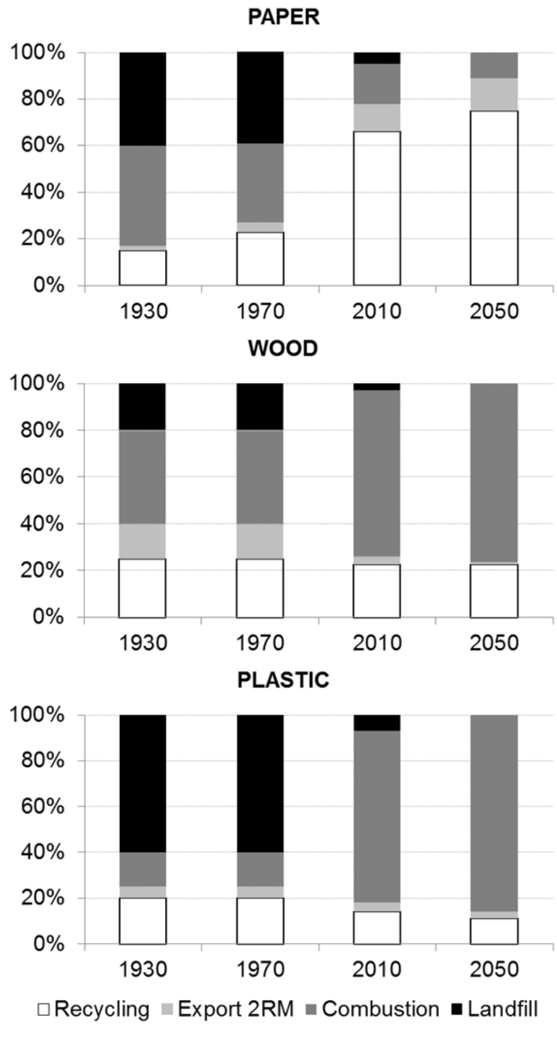


Figure 30: Estimated post-consumer waste treatment distributions in Germany

Three main waste treatments are available: recycling, incineration and landfill. Landfill was banned in Germany in 2005 and it was the largest waste management practice before this year. Figure 30 gives an overview of the changes in the shares of waste treatment processes in Germany, and includes an expected value for the year 2050. The data is found in table A.8 in Annex A. The strong tendency of using waste for energy purposes is noticeable, while the use for material purposes, with the exception of paper is reducing. In the case of wood, this has been mostly caused after the Renewable Energy Act (or *Erneuerbare-Energien-Gesezt* (EEG) in German) which was initially oriented for the incorporation of wood waste as energy source. For instance, the recycling of wood goes mostly to energy use (78.3% in 2010) or to the manufacturing of boards like chip particle boards (CPB) among others (20.2% in 2010). This material use includes the exported fraction of recycled woods that has also decreased dramatically from 14.3% in 2001 to almost 0% in 2010 and other uses less than 0.5% (Mantau, 2012b). The energy use has increase from 52.1% in 2001 to 78% in 2006 keeping this level up to 2010, while material use is decreasing from 39.5% in 2001 to around 21% on the years between 2006 and 2010.

Nearly 1.7 Mt of paper post-consumer wastes are incinerated in Germany because of incorrect waste separation (FÖP and Ökopol, 2013; COST, 2010). Nevertheless, the recovery rates of recyclable materials have reached nearly 70% in waste volume for both recycling and energetic purposes. In 2011 the recycling rate of recovered paper was 76% and the use of domestic purposes was around 71%. This is the actual volume of material used for manufacturing new products (FÖP and Ökopol, 2013; Kibat, 2012).

For plastic products, a change in the waste treatment processes is highly noticeable. Before 2005, the most frequent process was landfilling, followed by material recycling and finalizing with incineration (Patel et al., 2000). However, after 2005, landfill is reduced to 10%, while material use increases to around 21% and energy around 69% (TECPOL, 2008). A growing volume of plastics is used in electronic applications also challenges the waste allocation. For instance, recycling of plastics from Waste Electrical and Electronic Equipment Directive (or WEEE) have limited market for secondary material as they contain brominated flame retardants (Martens, 2011d; Banks, 2001). This should be removed from the electronic waste before being recycled (Martens, 2011d; Kozlowski, 2006). Finally, no changes in consumption patterns and a constant product matrix composition were assumed. The results of the baseline scenario are discussed below.

### 5.3.1. Raw materials requirements

Raw materials are used in the product manufacturing sector for the production of final goods. Nowadays, 69.7 Mt of carbon-based raw materials are required for the satisfaction of need in the German anthroposphere, and are calculated to grow to 96.3 Mt by 2055. From these requirements nearly three-quarters come from primary sources and one-quarter from secondary sources. The raw material requirements for the evaluated carbon-based industries in Germany are displayed in the left column of figure 31. Figure 31-A[5] indicates the total raw material (TRM) requirements for each of the carbon-based materials. Figure 31-B illustrates the primary raw material (PRM) requirements and figure 31-C the secondary raw material

[5] The estimation of the AMS dynamics is a combination of historical and modeled data. The source of information for the estimation of the model dynamics is indicated in figure 31-A. The period between 1929 and 2014 is based on historical time series (for better presentation of results these are presented from 1950 on) and the period between 2015s2055 is estimated with a scenario approach. This configuration is valid for all figures ahead.

(SRM) availability for the material groups, respectively. The figures in the right column of figure 31 illustrate the primary and secondary raw material distribution including its exports as discussed below.

The TRM volumes increment with rapid dynamics, with exception of wood. The demand of raw materials for the manufacturing of paper products will increase from 27.9 Mt in 2014 to 41.1 Mt in 2055 (a total of 49.4%). Similarly, plastics will also experience a dramatic boost hitting 30.1 Mt in 2055. This represents an growth of 107.5% compared to current values. On the contrary, the demand of wood stagnates with a contraction from 26.9 Mt to 23.7 Mt in 2055. Nevertheless, the demand of raw materials for wood products has been historically predominant being surpassed by the volumes for paper final goods in 2011 and by the demands of the plastic industry in 2043.

The difference between the TRM requirements for paper and plastic products begins with 3 Mt and grows until 13 Mt along the simulation, although the PRM volumes of both material groups are very similar (see figure 31-B). The PRM demand for plastics and paper products surpasses the wood volume almost simultaneously by 2040. The reason in the TRM difference comes from the larger SRM volumes from paper compared to the volumes from wood and plastics, as presented in figure 31-C. The SRM volumes for paper and wood present slow dynamics, while plastics display a steeper growth. Post-consumer wastes from paper are the largest source for carbon-based SRM providing around 15 Mt constantly per year. It is followed by wood with a growth between 3 Mt to 4 Mt and finalizing with plastics which provide between 2 Mt and 3.6 Mt of secondary raw materials to manufacturing sector.

Looking at the figures of the right column, figure 31-D provides a distribution between the primary (gray area) and secondary raw materials (black area) for paper, including the exported fraction of recovered paper (white area). In general terms, despite the large recycling rates, the PRM fraction will remain as the largest share mainly because of SRM volume stagnation. Paper SRM peaks around 2005 with a continuous decrease in the SRM fraction reaching 32% by 2055. It is observed that for wood and plastics the SRM fraction is not higher at any time than 20% of the TRM, as seen in figures 31-E and 31-F, respectively. Nevertheless, SRM for wood display a slight increment, while plastics present a downturn in the SRM share along the simulation. The use of plastics recyclates also indicates a decreasing tendency coming to 14% in 2055, while recovered wood reaches 19%. A large potential for increasing the material use of domestic post-consumer waste is observed for plastics and wood. Recovered paper has reached almost a saturation point with no large further expansion.

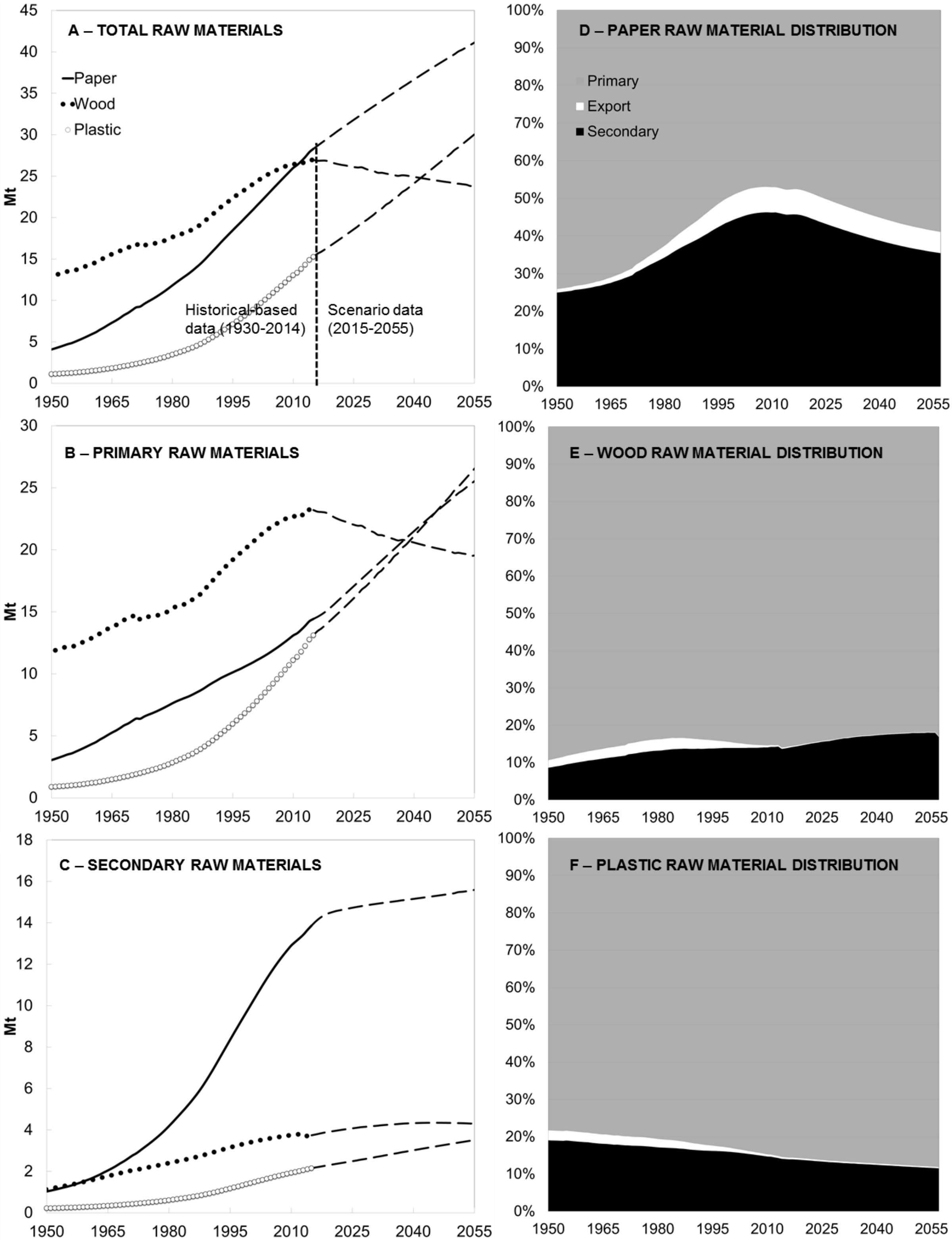


Figure 31: Required volumes of total, primary and secondary raw materials and corresponding distribution for material purposes, Mt

## 5.3.2. Total production and foreign trade

The total production illustrated in figure 32 combines the production of final goods for domestic and foreign markets. Figure 32-A reproduces with high fidelity the TRM behavior and dynamic requirements (see figure 31-A) considering the calculated manufacturing efficiencies for each of the material groups. An additional curve describes the use of wood final goods for energy purposes. The production volume of paper and plastic industries surpasses the wood production volume by 2020 and 2045, respectively. The paper production will grow to 34.1 Mt in 2055, while the plastic industry will be manufacturing nearly 27.6 Mt of goods in the same year. On the contrary, the wood industry will decline its material production volumes to 22.4 Mt, but it will have a slow growing dynamic production for final goods for energy purposes of 12.3 Mt by 2055. Thus, the wood industry manufacturing capacities will allocate around 50% for the production of final goods for energy purposes. The thin line in figures 32-A to 32-C describe the final wood products destined for energy use (noted as "Wood (E)" in the figures) of the total wood production and foreign trade.

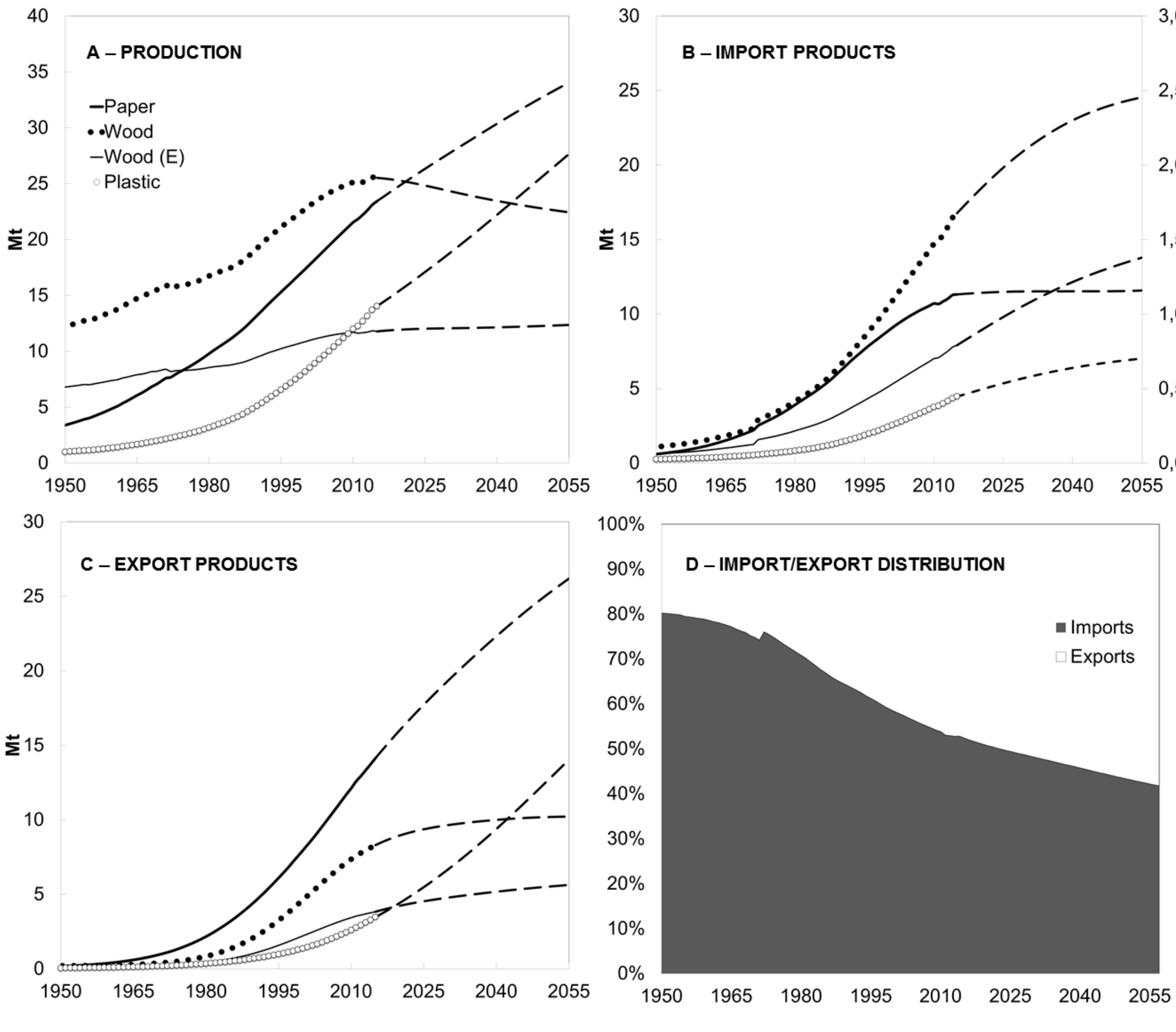


Figure 32: Total production, export and import flows and distribution, Mt. Comments: Wood (E)=wood for energy goods. Use secondary axis for imports flows of plastics in diagram B.

Figure 32-B shows the stagnated importing needs of paper products, while in figure 32-C a staggering volume of exported paper products is perceived (almost doubling the exported volumes in 35 years). In other words, the domestic demand of paper products has attained a saturation level. On the other side, imports of plastic and wood products, have a continuous growing trend as seen in figure 33-A. Nearly 25 Mt of wood products (including final goods for energy purposes) will be imported by 2055. In fact, the import volumes of final wood products are clearly larger than the exported volumes, confirming the situation of Germany as net wood importer (ETTF, 2011). On the other hand, the volume of imported plastic final products is currently 0.5 Mt and will maintain a very low volume with barely 0.71 Mt in 2055, as most of the imported plastic material to Germany comes for manufacturing processes. The dynamic of wood exports is slower and tends to level-off after 2026, as seen in figure 32-C. Further, the use of wood is switched to energy uses, as both curves become closer along the simulation. Since 1950 the country has been expanding its export share and now enjoys, for the evaluated carbon-related products, the state of net exporting nation as observed in figure 32-D.

### 5.3.3. Domestic consumption

As described in figure 29, the per capita consumption for each of the material groups in Germany and worldwide have in general increasing trends. In Germany, despite the shrinking population dynamics, it is seen in figure 33-A a development in the total consumption of goods from the current 65.3 Mt of final goods to 70.9 Mt in 2055. These volumes are discriminated in paper (31.7%), wood (51.7%) and plastic products (16.6%), and maintain a similar distribution until the final modeling year. Nevertheless, the calculated consumption volumes of paper products stagnate drastically around 19.4 Mt, very close to current volumes of 20.6 Mt (VDP, 2013b), despite the continuous growth in the domestic per capita consumption that reaches 275.6 kg paper/cap in 2055. It is still seen in figure 33-A a high domestic consumption volumes of wood, despite the perceived reduction in the TRM requirements of this material, with a slight leveling-off in the coming decades at around 36.9 Mt. From this consumption, final goods for energy uses have the largest share with circa 20 Mt in 2055. On the other side, the consumption of plastics will have a growing dynamic attaining 14.4 Mt by 2055.

As consumption of goods seeks the satisfaction of needs through products that provide specific services, the consumption dynamics are categorized in this way. Figures 33-B to 33-D describe the domestic demand in terms of services. A notable change occurs within the paper products with the service of communication as it suffers a dramatic cutback of almost 50% in 2055 compared to 2014. This means that the market share of this service reduces from 48.1% (9.9 Mt) in 2014 to 24.1% (4.9 Mt) in 2055. The critical reduction in the use of graphic paper in the future has been discussed in industry reports (Dispan, 2013b). Conversely, the service of well-being is doubling the consumption from 3.2 Mt in 2015 to 6.8 Mt in 2055. This growing dynamic compensate the reduction in the service of communication and it is reflected in the stabilization of the total domestic demand, as identified in figure 33-A. On the other side, services like packaging present a very slow but constant dynamic around 7.7 Mt since 2030 on.

While all the material services for wood products declines or languish, final goods for energy purposes (not shown in the graph) grows constantly along the periods achieving nearly 20.7 Mt in 2055. This is equivalent to 56% of the total use of wood. Signs of decrease in the demand of wood for capital goods is seen in figure 33-C. While residential and non-residential services have a very likely pattern, the service of well-being appears to reach a peak and initiate a parallel decline along the other two services. The domestic demand of wood is much larger in non-residential than residential, but both are in the order of four to five million tons per year. The packaging service with wood products faces a stagnation keeping volumes around three million tons per year. Although, these services show a reduction in the consumed volumes, the total domestic consumption of wood maintains a growing trend as the consumption of final goods for energy purposes keeps enlarging from todays 15.9 Mt to 20.9 Mt in 2055.

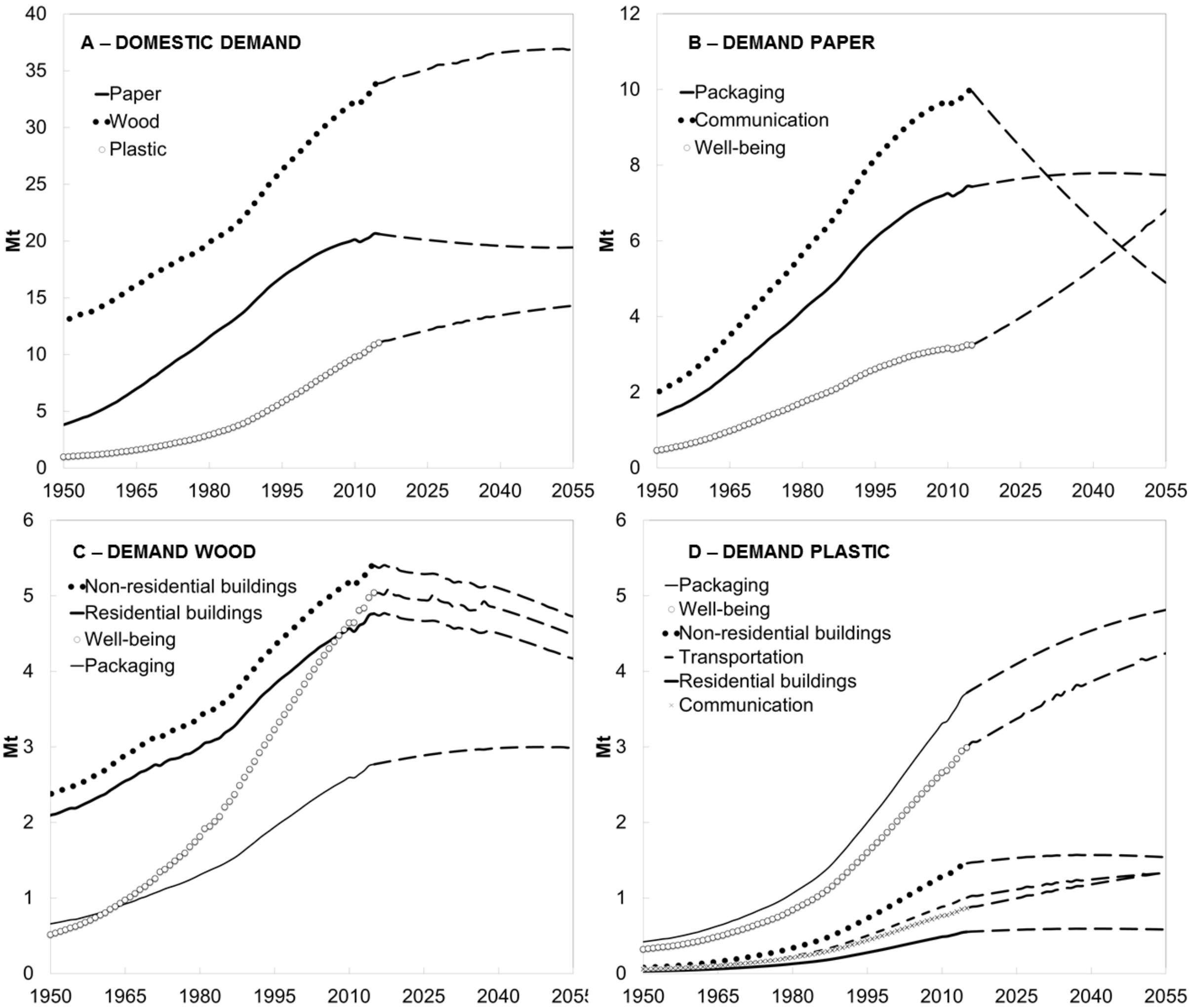


Figure 33: Domestic demand in Germany per material groups and services for carbon-based materials, Mt.

The demand for plastic products in figure 33-D, exhibits a rapid dynamic for almost every service with consumer goods. The largest plastic service is the packaging sector with a domestic demand increase of nearly 3.7 to 4.8 Mt during the simulated periods. This service is followed very closely by the well-being service both with distinct growing dynamics. On a lower scale the demand of plastics for transportation and communication also experience a continuous growth reaching both 1.3 Mt. On the contrary, the use of plastic in dwellings and non-residential constructions seem to level-off very quickly at 0.6 Mt and 1.5 Mt. Finally, because of the very low material demand in infrastructure services coming from carbon-based materials, these curves are not included in figures 33-C and 33-D. The domestic demand of plastic products for infrastructure is around 450 kilotons (kt) per year and of wood an annual volume of circa 50 kt for the whole period between 2015 and 2055. The consumption values of the service infrastructure for the baseline scenario are presented in figure A.2 in Annex A.

### 5.3.4. Stock dynamics

Figure 34-A illustrates the stocks dynamics for each of the material groups and figure 34-B describes the distribution of the anthropogenic carbon stocks per services and materials along the simulation. Currently a total of 413.1 Mt of carbon-based material stocks are in-use in Germany. From these 32.6 Mt are paper goods (7.9%), 304.6 Mt wood products (73.7%) and 75.9 Mt to plastic products (18.4%), which indicates a stock per capita of 398 kg of paper, 3.8 tons of wood and 951 kg of plastics, respectively. Growing directions in all material stocks are seen. Wood stocks build-up at a relative constant rate to peak in 2040, where they begin to shrink. On the contrary, plastics stocks dynamics show a growing trend along the simulation period and will reach 114.5 Mt by 2055. This is equivalent to 1.6 t plastics/cap in Germany in 2055 and represents an increment of 68.2% compared to 2014. Paper stocks will suffer a loss with no signs of growth, touching its lowest in 2055 with 16.8 Mt. In 2055, stocks will totalize 480.6 Mt represented by 3.6% of paper, 72.7% of wood and 23.8% of plastic stocks. In figure 34-B, the three largest anthropogenic carbon stocks groups are in the services of residential, non-residential and well-being, where wood occupies the largest share (plain filling in the graph) among the materials. Until 2055 the built environments will continue to be the largest responsible of carbon-based material stocks in the German anthroposphere with nearly 72% of the whole stock share. This share however suffers a reduction compared to 1950 where almost 85% of the carbon-based material stock was wood. The use of wood for built environments will continue, but due to the expected deceleration of construction stocks will shrink by 2055 in around 13% compared to 1950. These three groups dominate largely, while communication, transport and packaging rely in the back with less than 10% of the total stocks. From these small services, it is recognized a growth in the transportation service. Further, stocks dynamics are seen in the packaging sector, especially the paper products. The use of paper in communication is drastically reduced. With this tendency, the use of paper for this service could disappear by 2085. The overcome of plastics indicates a larger stocks of plastic uses in the communication service with a change of 1.5-fold compared to 2015, increasing from 5.2 Mt to 8.1 Mt.

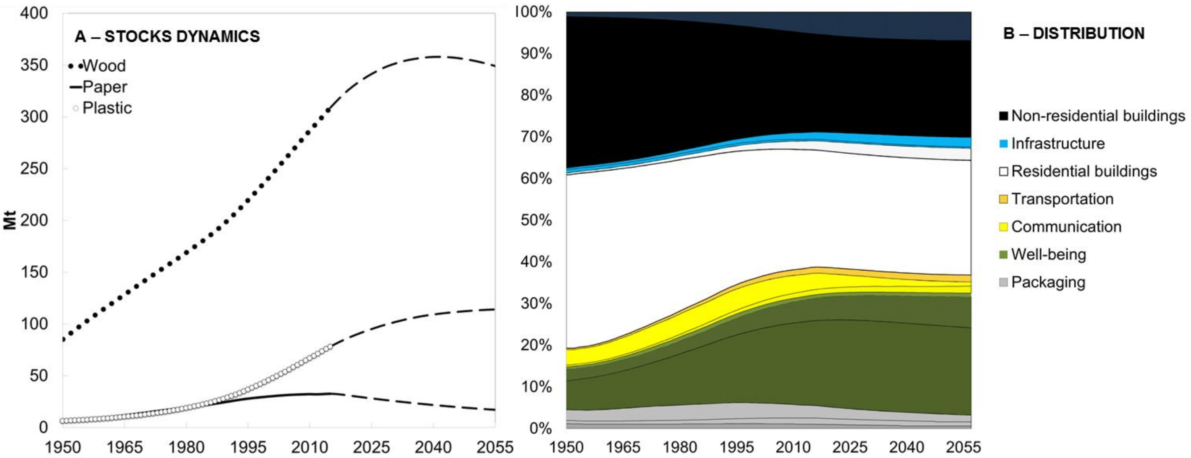


Figure 34: Stocks dynamics (Mt) and distribution (%) of anthropogenic carbon stocks per material group and services. Comments: In diagram B, plain filling: wood; line filling: paper; square filling: plastic

Figures 35-A to 35-D summarize the stocks dynamics according to services and material groups. Figure 35-A describes the stocks dynamics of communication and transport services. As imagined, the consequent reaction of these stocks to the consumption dynamics is clearly identified. The use of paper for communication will decline 71.8% in the following four decades to attain 4.7 Mt in 2055. On the contrary, plastics will increment by 57% with 8.1 Mt in the same year. Nevertheless, the rapid shrinkage in paper communication stocks is compensated with a rise in the plastic communication stocks, which by 2044 will have a larger stock in-use in the material system. On the other side, an addition in the plastics stocks for transportation is seen from a current volume of 5.9 Mt to 8.0 Mt in 2055.

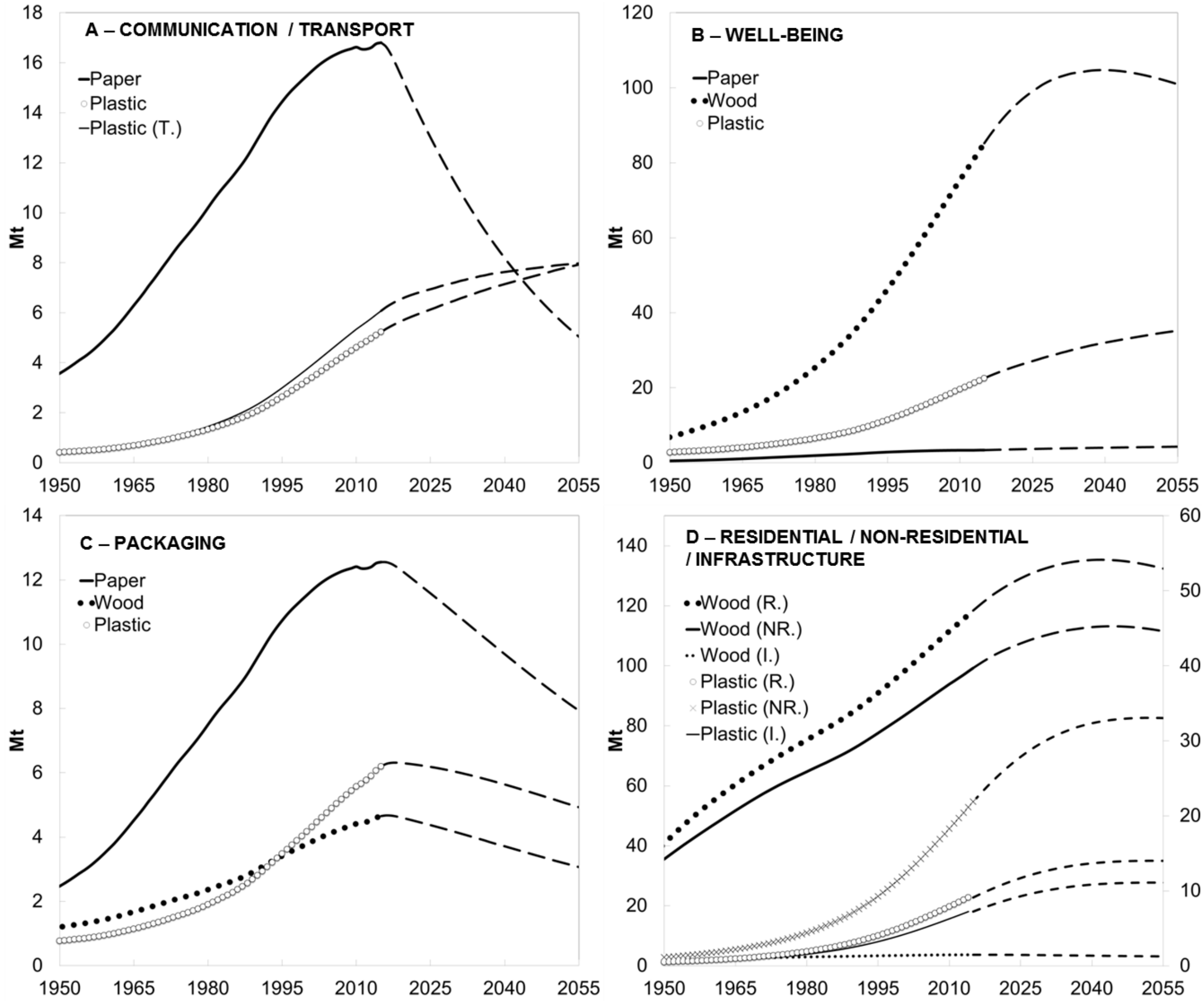


Figure 35: Stock dynamics of anthropogenic carbon stocks per services and material groups, Mt.

Figure 35-B illustrates the stocks from well-being services mostly represented by furniture and other wood and plastic products (musical instruments, toys, household items, and so on). Wood stocks follow a very comparable behavior as the one observed in the capital stocks in figure 35-D. On the other hand, plastic stocks will hit 35.6 Mt in 2055, in a continuous growth. Figure 35-C presents the reduction of stocks in packaging service. The stocks of packaging will reduce from 23.2 Mt in 2014 to 15.5 Mt, with the largest loss in paper packaging. Finally, figure 35-D describes the stocks dynamics of built environments that is dwellings, infrastructure and non- residential buildings. Wood has the larger stocks however

the growth of plastics stocks should not be ignored reaching in 2055 almost 13.9 Mt in residential constructions and 32.9 Mt in non-residential constructions. In built environments, the use of plastic will grow, replacing in many cases wood products; however, these changes shall occur mostly in indoor areas. Finally, the use plastic stocks in infrastructure will grow with a slow dynamic to attain 11.1 Mt with signs of stagnation after the year 2035. Wood stocks in infrastructure are constantly below 1.5 Mt and will continue to reduce along the whole simulation.

In short, paper stocks will suffer a reverse in the coming decades and will shrink from 32.6 Mt nowadays to 16.8 Mt in 2055. Wood stocks will continue to grow at least for 30 more years peaking at 357 Mt. The rapid dynamic of plastics and its even wider use in consumer and capital goods display a continuous increase of plastics stocks for the coming 40 years.

### 5.3.5. Post-consumer waste

The post-consumer waste volumes of the material groups in figure 36-A show first expanding tendencies for plastics and wood and also a clear stagnation for paper. A total of 42.1 Mt of post-consumer waste (excluding wood for energy use) is currently generated and will develop to around 51.5 Mt in 2055. The largest share comes from the paper products with 20.3 Mt (48.2%), followed by the wood products (excluding final goods for energy purposes) with 13.3 Mt (31.6%) and closing with a volume of plastics waste of 8.4 Mt (19.9%). Post-consumer waste flows of wood and plastic will continue to increment attaining levels of 17.5 and 14.2 Mt, respectively in 2055. This means a rise of 31% for wood and 68% of plastics compared to 2014. For paper products, a volume around 20.8 Mt is calculated in the coming years and a slight downturn after 2030 is seen to hit 19.7 Mt in 2055. By this year, total post-consumer waste will add 51.37 Mt with shares of paper (38%), wood (30%) and plastic wastes (32%).

The distribution of post-consumer wastes in terms of services are shown in figure 36-B. As expected, the largest waste shares come from the packaging services with 32%, well-being services with nearly 28% and communications services with 13% approximately. Thus, a total of 73% of the post-consumer waste outflows belong to short or middle in-use lifetime consumer goods. An upturn of plastic post-consumer flows compared to the paper and wood flows is perceived in almost all the services. But especially in the communication and the well-being service were a considerable reduction in paper waste might happens. In fact, waste outflows for paper communication will decrease from 9.8 Mt to 4.8 Mt, while for plastics boosts from 0.8 Mt to 1.3 Mt along the simulation and matches to the stock dynamic pattern. On the other hand, the post-consumer waste from capital stocks (built environments and infrastructure) remains constantly below 20%.

Post-consumer wastes in terms of services are described in figures 37-A to 37-D. In figure 37-A post-consumer wastes from communication with paper products cutback from 9.9 Mt to 4.9 Mt, while the same service with plastic increments from 740 kt to 1.3 Mt in 2055. In this same figure the use of plastics in transport service is presented, and it also presents an expanding trend reaching a similar volume of communication waste of 1.3 Mt. The communication post-consumer wastes will shrink by 49%, while paper for well-being will increase by 119% to a level of 5.7 Mt in 2055. Conversely, to the declining flow of communication with paper products on figure 37-B, a steep rise in the wastes from well-being from the same material is distinguished, becoming the largest waste material for this service in the final years of the simulation. The post-consumer waste of packaging in figure 37-C also stagnates in current levels in all materials with a total of 15.8 Mt in 2055 distributed in paper with 7.8 Mt (49%), wood with 3.1 Mt (19%) and plastics with 4.9 Mt (31%). Plastics wastes for packaging will grow 40% compared to 2014, and will become the second most used material from 1995 on. Wood does not show a rapid development like plastic packaging. In fact, both paper and wood wastes for packaging will have very low dynamics of 7% and 13%, respectively.

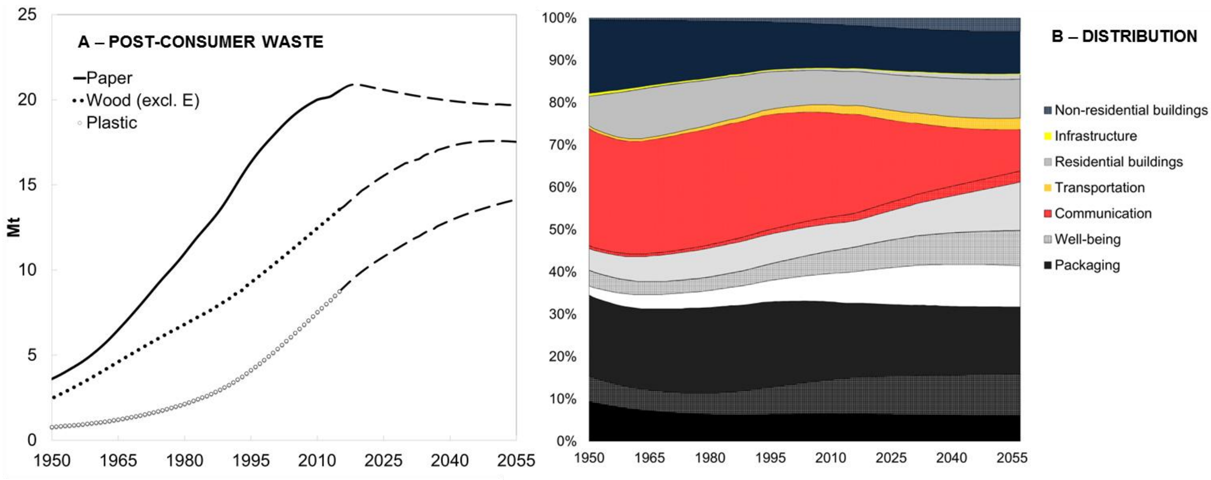


Figure 36: Total post-consumer waste (Mt) and distribution (%) per material groups and services, Mt. (Comments: In diagram B Plain filling: wood; line filling: paper; square filling: plastics)

Despite the possible reduction in the dynamics of construction, figure 37-D indicates that the flows of debris and demolition wastes will continue to develop substantially attaining 6.5 Mt from dwellings and 5.1 Mt from non-residential buildings. Plastics, in special, will have a fast dynamics and will reach 2.2 Mt in 2055, mostly coming from the non-residential buildings.

Post-consumer wastes can also be described in terms of processed raw materials as shown in figure 38. The volumes of raw materials are defined with the information from the production function matrix (see section 4.4). This information describes the reach for recycling and potential use of SRM. For instance figure 38-A shows plastic post-consumer wastes volumes. A volume of 1.8 Mt of low density polyethylene (LDPE) is calculated for 2055. This means an increase of 51% compared to 2014. Another relevant polymer used very frequently in built environments is polyvinylchloride (PVC), with nearly 1.5 Mt in 2055. All polymers will raise their post-consumer wastes at least by 40% along the simulation. On the other side, post-consumer wood waste is illustrated in figure 38-B. Stagnation in chemical pulp is observed around 14 Mt, while a decrease in the volumes of mechanical pulp peaking in 2020 with 2.3 Mt reaches 1.8 Mt in 2055. Post-consumer sawnwood wastes will continue to increment almost linearly until 7.1 Mt in 2055. The other wood wastes present stagnation along the final periods.

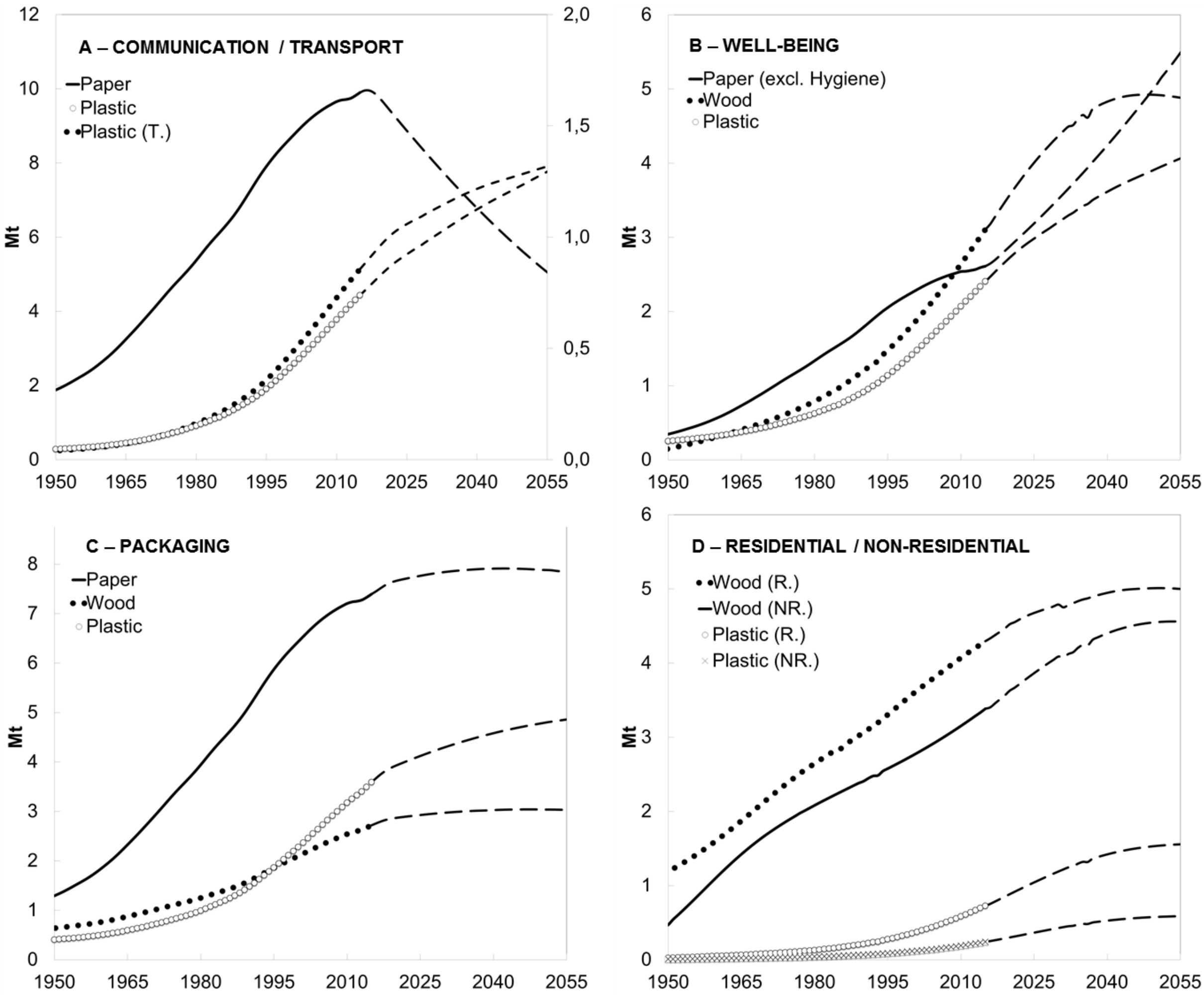


Figure 37: Post-consumer wastes per services, Mt. (Right axis for plastic flows in figure A)

A growth in the post-consumer waste outflows volumes, especially in plastic products is observed. Wood waste outflows have by far the largest carbon-based material waste distribution, but will face a slight stagnation in the last modeling decade (2040-2050). Despite the drastic reduction of paper waste for communication, the volumes of paper post-consumer waste will remain constant, as new application and special uses for paper are being developed.

### 5.3.6. Carbon-related emissions

Carbon-based materials are carbon sinks that bound elementary carbon during its complete in-use lifetime. A total volume of 92.1 Mt $CO_2$-eq of carbon material-related emissions are released nowadays to the atmosphere and these will continue to rise crossing the 100 Mt $CO_2$-eq level around 2031. The current total carbon emissions are the sum of four sources: (1) the incineration of carbon-based post-consumer waste in waste treatment processes (36.1 Mt $CO_2$-eq), (2) the combustion of final goods for energy purposes (25.2 Mt $CO_2$-eq). The other two sources are (3) the combustion of residues or by-products from the product manufacturing sec- tor used as energy sources (12.4 Mt $CO_2$-eq) and (4) the emissions from the decay of discarded products in form of methane in landfills (18.4 Mt $CO_2$-eq).

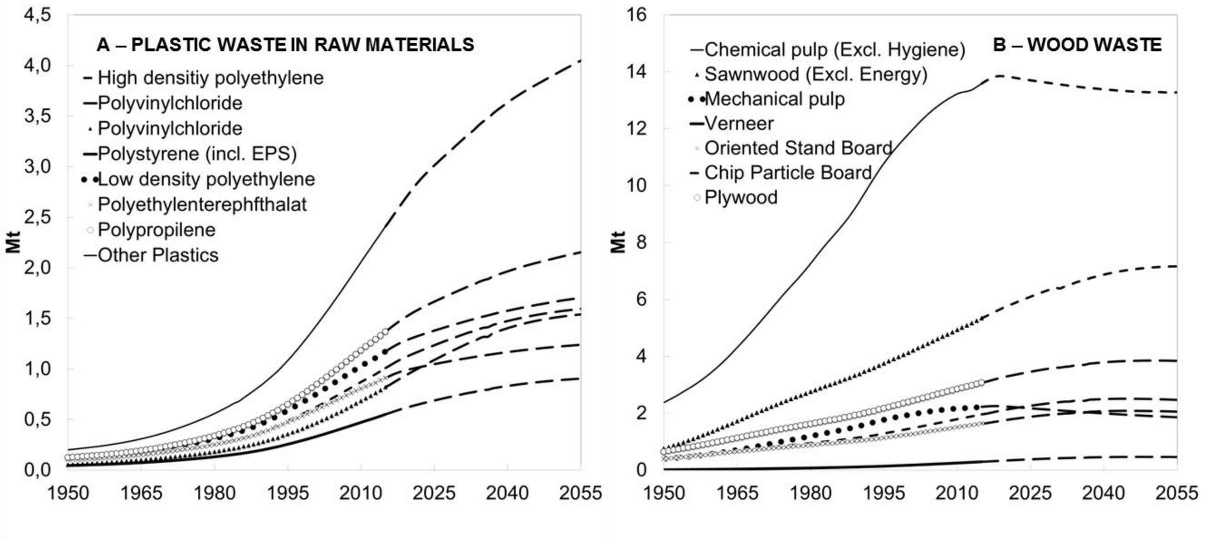


Figure 38: Post-consumer plastic and wood-based waste outflows per raw materials, Mt

In figure 39-A as a result of the landfill ban in 2005 in Germany, the emissions from landfills peaked in 2001 with a subsequent continuous annual contraction. The landfill carbon emissions will reduce by 315% in 2055 compared to the emissions of 2001 (22.8 Mt $CO_2$-eq) and will match plastic emissions from incineration processes in 2019 and carbon material-related emission from manufacturing processes in 2024. These two latter emission sources will continue to rise. From the material groups, paper loses almost 55% of its contribution and plastic increases 1.8-fold to reach 26.9 Mt $CO_2$-eq in 2055. As seen in the upper-left diagram in figure 39-A, emissions from wood products (including final goods for energy purposes) will remain as the largest contributor from the whole carbon-related emissions volume (lower light gray area), where almost 50% is originated from direct use for energy purposes. At the same time it is perceived the dramatic expansion of plastic-originated emissions (white area) from 4% in 1990 to 23% in 2055.

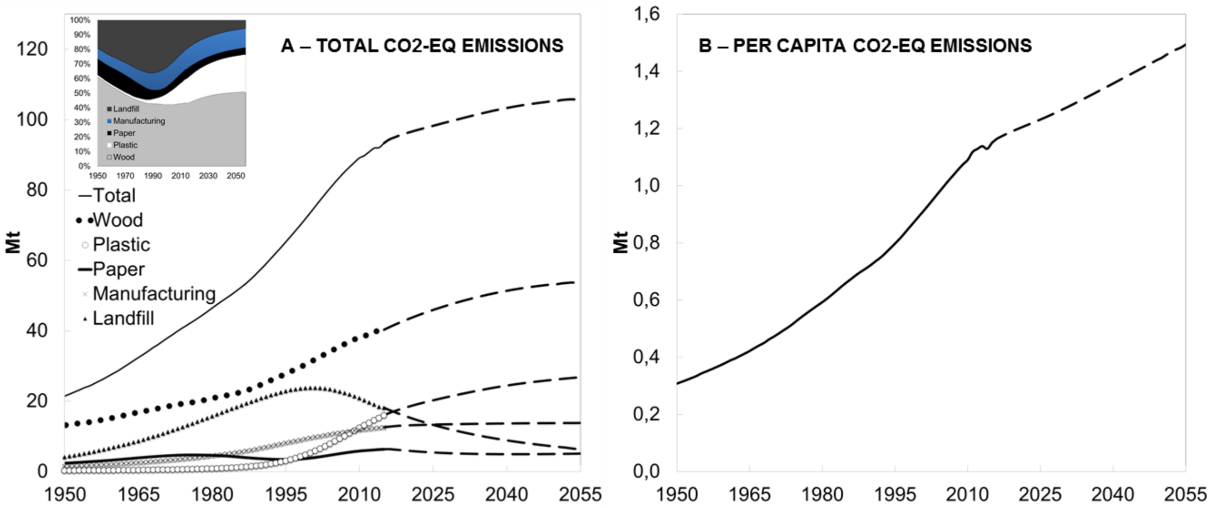


Figure 39: Total and per capita carbon emissions from manufacturing, landfill and combustion processes of carbon-based final goods, Mt $CO_2$-eq.

In terms of carbon emissions per capita, the total contribution from anthropogenic carbon-based products, including final goods for non-industrial energy purposes, will continue to grow. Carbon emissions will continue to rise, with a growing share from non-renewable sources. In 2014 a total of 1.14 Mt $CO_2$-eq /cap were emitted and will rise to 1.48 Mt $CO_2$-eq /cap by 2055 as observed in figure 39-B. This is caused by the dynamics shown in figure 39-A, but also as a result of the population dynamics, as it shrinks continuously.

## 5.4. Model validation using baseline scenario results

The comparison of independent historic available data provides an additional confidence and trust to the modeling process, providing reliability in the results. With a model capable of providing accurate past behaviors, it can be inferred that future results convey within a better confidence interval. Several past results were compared with the model to obtain a full spectrum of its capacity of prediction. Because of the difficulty in the reporting units, product classification and definitions, differences appear between the reports. For example, for Schiller et al. (2015) vehicles are not consumer goods but capital goods. Polymers are clearly described within built environments in Deilmann et al. (2014), while in the former report these are presented in a general category "Plastics". Thus, the results presented here provide a general overview of the reliability of the model. If possible a detailed analysis of specific consumer or capital goods is presented.

Figure 40-A compares the historic results (Consultic, 2013) from plastic post-consumer wastes in 2013. Figure 40-B does the same for wood-based wastes (Mantau, 2012b), including paper wastes (VDP, 2012). The literature describes in 2010 a total of 8.1 Mt of available waste wood. For the same year the model estimated 12.3 Mt. As seen the model reports a waste volume of 15.9% larger for plastic and of 6.8% for wood-based materials. The product distribution share, however, is comparable. As said in section 3.3.4, the model has omitted the operational flaws at recovery and distribution phases where material losses occur, leading to undesirable littering. This problem might contribute to the differences found between the model and the reported data.

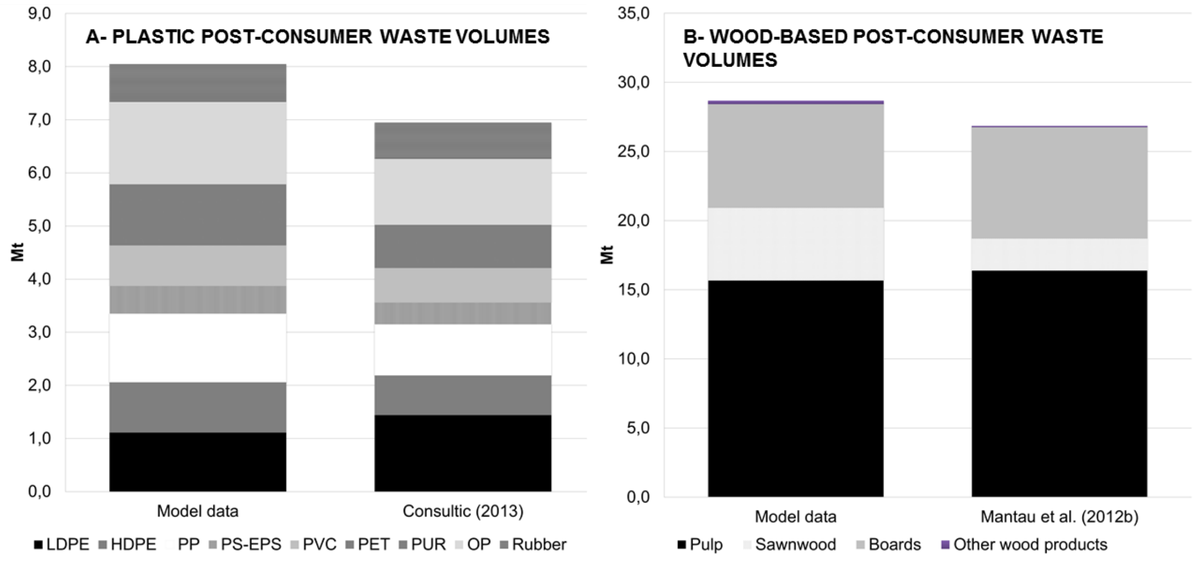


Figure 40: Comparison between model and historical results in 2013 for carbon-based post-consumer wastes. LDPE=Low density polyethylene, HDPE=High density polyethylene, PP=Polypropylene, PS-EPS=Polystyrene (Expanded), PVC=Polyvinylchloride, PET=Polyethylene-terephthalate, PUR=Polyurethane, OP=other polymers.

A fundamental variable of the model is the estimation of in-use stocks along the carbon-based materials. A large volume of carbon stocks of wood and plastic mainly are used in built environments (dwellings and non-residential buildings). A comparison of the results in 2010 from the evaluated materials found in the literature (Deilmann et al., 2014) with the model results are illustrated in figure 41. Wood stocks are very comparable with the values estimated in other reports. Plastic stocks estimate a volume 54% lower than the literature. This difference in the plastic stocks is stressed by the fact that, as expressed in section 4.3.3., part of the plastic production is not taken into account. Almost a quarter of the plastic production is destined to the manufacturing of complementary applications (glues, paints, fibers, and so on) which are not tracked inside the AMS.

Thanks to the model granularity a more detailed level the comparison of specific data is also possible. For instance, the plastic use in the transport services was also compared. In 2006 the average volume of plastics in vehicles was 150 kg/vehicle (Kozlowski, 2006). In the model for the same year the estimated volume was 144 kg/vehicle. This corresponds to a difference of less than 4.3% between both results. The infrastructure service in Germany for 2011 reports an in-use stock of plastics of 11.0 Mt and of wood of 3.5 Mt (Schiller et al., 2015). The model estimates 6.9 Mt and 1.5 Mt, respectively. Further, in 2010 a volume of 0.57 Mt of plastic doors and windows were consumed according to the model. A report estimates nearly 0.48 Mt for these product groups (Deilmann et al., 2014) for the same year.

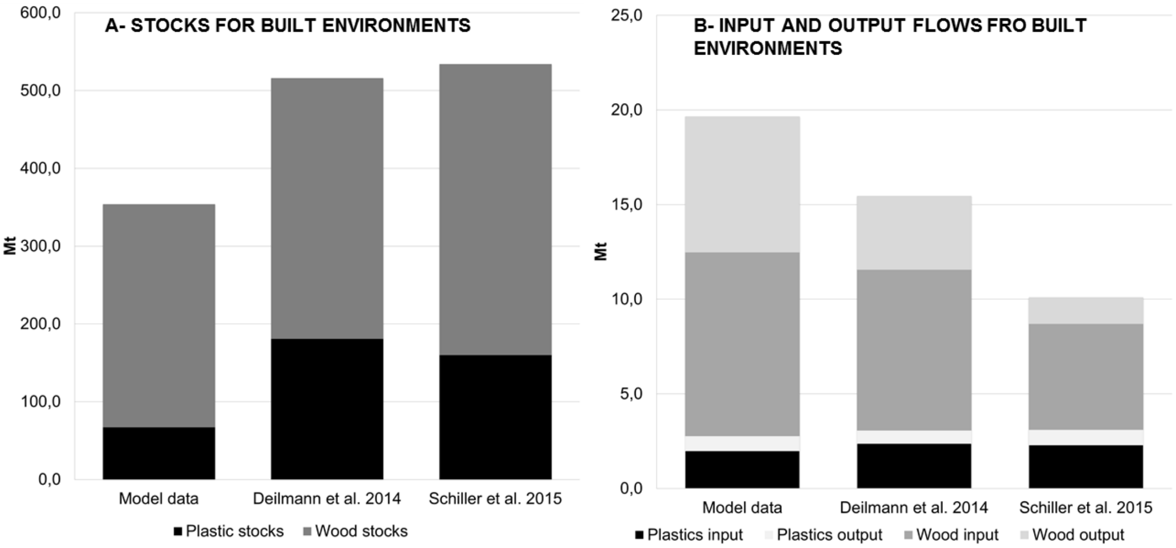


Figure 41: Comparison between model and historical results in 2010 for carbon-based in-use stocks and flows in built environments.

Further, the recovered paper rate in 2013 was 71%, while the share in the total domestic demand of paper is just 56% (FÖP and Ökopol, 2013). This value matches the estimated value obtained in the simulation of 52% as shown in figure 31. In terms of SRM the model estimated for 2007 a total of 17.8 Mt from wood-based sources and 1.83 Mt from plastic wastes. For this year 18.7 Mt and 4.8 Mt of wood and plastic SRM were determined in the literature (Schiller et al., 2015).

The observed differences within the values of material inflows and outflows, as well as in the total carbon stocks in the AMS between the reported data and the model are cause not only by information gaps and quality but by the analysis method used. Top-down or bottom-up approaches or a combination of both, have been employed. In general a top-down approach contains larger data uncertainties than the bottom-up methods and estimates larger volumes of materials (Schiller et al., 2015). Nevertheless, the developed EW-SFM shows reliable information for the use of prospective analysis under scenario approach.

Table 8: Minimum and maximum input values for the scenario approach in 2055

| Variable | 2014 | 2055 (–) | 2055 (+) |
|---|---|---|---|
| Per capita consumption (kg/cap) | | | |
| *Domestic* | | | |
| Paper | 254.8 | 219.1 | 279.1 |
| Wood - incl. energy goods | 429.2 | 452.9 | 532.9 |
| Plastic | 133.9 | 174.6 | 343.0 |
| *Foreign* | | | |
| Paper | 61.6 | 81.7 | 147.0 |
| Wood - excl. energy goods | 280.6 | 260.0 | 478.0 |
| Plastic | 46.9 | 109.2 | 139.2 |
| Manufacturing efficiency (%) | | | |
| Paper | 0.82 | 0.82 | 0.90 |
| Wood | 0.93 | 0.93 | 0.95 |
| Plastic | 0.92 | 0.92 | 0.95 |
| Recycling efficiency[a] | | | |
| Paper | 0.95 | 0.95 | 0.95 |
| Wood | 0.80 | 0.80 | 0.95 |
| Plastic | 0.90 | 0.90 | 0.95 |
| Waste management distribution (%) | | | |
| Paper (recycling[b]) | 82% | 89% | 95% |
| Wood (recycling) | 25% | 24% | 42% |
| Plastic (recycling) | 16% | 14% | 32% |
| Paper (incineration) | 18% | 5% | 11% |
| Wood (incineration) | 75% | 58% | 77% |
| Plastic (incineration) | 83% | 68% | 86% |
| Landfill | 1% | 0% | 0% |
| Service-based lifetime change[c] | | | |
| Packaging | 1.0 | 0.8 | 1.2 |
| Well-being | 1.0 | 0.8 | 1.1/1.2 |
| Communication | 1.0 | 0.8 | 1.1/1.2 |
| Transport | 1.0 | 0.8 | 1.2 |
| Non-residential commodities | 1.0 | 0.8 | 1.1 |
| Residential commodities | 1.0 | 0.8 | 1.15 |
| Non-residential dwellings | 1.0 | 0.8 | 1.0 |
| Residential dwellings | 1.0 | 0.8 | 1.0 |
| Infrastructure | 1.0 | 0.8 | 1.0 |

*Comments:* a) Fraction of recycled materials during recycling process; b) Includes exported fraction; c) n-fold change

The baseline scenario describes a potential future development of the AMS in the studied region. It shows a continuous increment in raw materials requirements in the paper and plastic industry. The domestic demand shows also a growing dynamic, as well as a built-up in wood and plastic stocks. Larger volumes of post-consumer wastes are observed and the increase of per capita emissions, create a burden for the environment and a possible challenge within the political sphere. Using this scenario as reference a number of alternative scenarios are evaluated with the aim of creating a wide panorama of action in order to provide a perspective in improving circularity.

## 5.5. Alternative scenarios

Within the seven alternative scenarios strategies for dematerialization (reduction of materials with same service output), substitution of materials or inclusion of new ones, effects in changes in consumption patterns, improvement in the waste treatment recovery and recycling chain, among others are considered and discussed within each scenario accordingly. Seven alternative scenarios are proposed; some focus on specific actions *ceteris paribus*, while other combine several variables all within the goal of understanding the dynamics of AMS in the purpose of achieving a better circularity. The alternative scenarios provide hints of possible AMS developments in Germany, offering several outcomes and changes within the material system on key variables for the description of the material systems. These are (1) total, primary and secondary raw material requirements, (2) production volumes, (3) stock dynamics, (4) post-consumer wastes and (5) carbon-related emissions. All the variable changes in the alternative scenarios begin in 2015 and remain until 2055. The initial year was selected as the historical data regressions finished in 2014. The ranges of the variables within the scenarios are summarized in table 8. The final year (2055) is tabulated with its lowermost and uppermost values. Further, initial values of 2014 are provided for comparison purposes and to give an idea of its dynamics along the simulation. A fully description of each scenario is provided in table 9. This summarizes the final values for year 2055 to describe the changes of input values in each alternative scenario, compared to the baseline scenario.

The scenarios are named according to the investigation interest. The scenario "Recycling" evaluates the response to a notable rise in the recovery rates and recycling efficiencies of the carbon-based materials. The scenarios "Reuse" and "Refuse" investigates the effects of change in consumption patterns expressed in an extension or shortening of the in-use lifetime of products and changes in domestic per capita consumption volumes. The scenario "Circularity" combines the parameters of the scenario "Recycling" and "Reuse" with the intention of creating a best-case scenario for AMS cycles. Because the use of plastic shows signs of increment worldwide, the scenario "Substitution Plastic" studies the replacement trend of paper and wood products for plastic goods, keeping current recycling rates. On the same perspective, the scenario "Substitution Plastic +" considers the increase of plastic consumption and answers the effects after improvements made by better recycling plastic strategies. Finally, the scenario "Foreign" assumes a staggering (and possible) increment in the foreign per capita consumption worldwide of products to evaluate the impact in the German AMS. Foreign consumption is assumed to reach the average consumption levels of the European Union. Each scenario is described in greater detail as follows.

### 5.5.1. Scenario "Recycling"

Recycling of materials for SRM supply is considered a major process for coping resource and emissions pressures (UBA, 2009). The recycling of paper in Germany is almost peaking deployment with current levels of recovery rates of between 77-82% and 72-77% of final SRM use in new products with limited options for improvements (Kibat, 2012). On the other side,

Table 9: Comparison and changes between Baseline and alternative scenarios in 2055

| | Scenarios | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Variable | Base-line | Recy-cling | Reuse | Refuse | Circu-larity | Substitution | Substituion+ | Fo-reign |
| Per capita consumption (kg/cap) | | | | | | | | |
| Paper (domestic) | 279.1 | 279.1 | 233.2 | 334.6 | 233.2 | 219.1 | 219.1 | 279.1 |
| Wood (incl. E)(domestic) | 532.9 | 532.9 | 516. | 559.3 | 516.7 | 452.9 | 452.9 | 532.9 |
| Plastic (domestic) | 203.0 | 203.0 | 168.7 | 239.4 | 168.7 | 343.0 | 343.0 | 203.0 |
| Paper (global) | 91.7 | 91.7 | 91.7 | 91.7 | 91.7 | 81.7 | 81.7 | 147.0 |
| Wood (excl. E) (global) | 280.0 | 280.0 | 280.0 | 280.0 | 280.0 | 260.0 | 260.0 | 478.0 |
| Plastic (global) | 109.2 | 109.2 | 109.2 | 109.2 | 109.2 | 139.2 | 139.2 | 136.0 |
| Manufacturing efficiency (%) | | | | | | | | |
| Paper | 0.82 | 0.82 | 0.82 | 0.82 | 0.90 | 0.82 | 0.82 | 0.82 |
| Wood | 0.93 | 0.93 | 0.93 | 0.93 | 0.95 | 0.93 | 0.93 | 0.93 |
| Plastic | 0.92 | 0.92 | 0.92 | 0.92 | 0.95 | 0.92 | 0.92 | 0.92 |
| Recycling efficiency[a] (%) | | | | | | | | |
| Paper | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 |
| Wood | 0.80 | 0.95 | 0.80 | 0.80 | 0.95 | 0.80 | 0.80 | 0.80 |
| Plastic | 0.90 | 0.95 | 0.90 | 0.90 | 0.95 | 0.90 | 0.95 | 0.90 |
| Waste management distribution | | | | | | | | |
| Paper (recycling[b]) | 89% | 95% | 89% | 89% | 95% | 89% | 89% | 89% |
| Wood (recycling) | 24% | 42% | 24% | 24% | 42% | 24% | 24% | 24% |
| Plastic (recycling) | 14% | 32% | 14% | 14% | 32% | 14% | 32% | 14% |
| Paper (incineration) | 11% | 5% | 11% | 11% | 5% | 11% | 11% | 11% |
| Wood (incineration) | 77% | 58% | 77% | 77% | 58% | 77% | 77% | 77% |
| Plastic (incineration) | 86% | 68% | 86% | 86% | 68% | 86% | 68% | 86% |
| Landfill | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Service-based lifetime change[c] | | | | | | | | |
| Paper - Packaging | 1.0 | 1.0 | 1.2 | 0.8 | 1.2 | 1.0 | 1.0 | 1.0 |
| Wood - Packaging | 1.0 | 1.0 | 1.2 | 0.8 | 1.2 | 1.0 | 1.0 | 1.0 |
| Plastic - Packaging | 1.0 | 1.0 | 1.2 | 0.8 | 1.2 | 1.0 | 1.0 | 1.0 |
| Paper - Well-being | 1.0 | 1.0 | 1.1 | 0.8 | 1.1 | 1.0 | 1.0 | 1.0 |
| Wood - Well-being | 1.0 | 1.0 | 1.2 | 0.8 | 1.2 | 1.0 | 1.0 | 1.0 |
| Plastic - Well-being | 1.0 | 1.0 | 1.2 | 0.8 | 1.2 | 1.0 | 1.0 | 1.0 |
| Paper - Communication | 1.0 | 1.0 | 1.1 | 0.8 | 1.1 | 1.0 | 1.0 | 1.0 |
| Plastic - Communication | 1.0 | 1.0 | 1.2 | 0.8 | 1.2 | 1.0 | 1.0 | 1.0 |
| Plastic - Transport | 1.0 | 1.0 | 1.2 | 0.8 | 1.2 | 1.0 | 1.0 | 1.0 |
| Wood - Non-residential commodities | 1.0 | 1.0 | 1.1 | 0.8 | 1.1 | 1.0 | 1.0 | 1.0 |
| Plastic- Non-residential commodities | 1.0 | 1.0 | 1.1 | 0.8 | 1.1 | 1.0 | 1.0 | 1.0 |
| Wood - Residential commodities | 1.0 | 1.0 | 0.8 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 |
| Plastic - Residential commodities | 1.0 | 1.0 | 0.8 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 |
| Wood - Non-residential dwellings | 1.0 | 1.0 | 0.8 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 |
| Plastic - Non-residential dwellings | 1.0 | 1.0 | 0.8 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 |
| Wood - Residential dwellings | 1.0 | 1.0 | 0.8 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 |
| Plastic - Residential dwellings | 1.0 | 1.0 | 0.8 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 |
| Wood - Infrastructure | 1.0 | 1.0 | 0.8 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 |
| Plastic - Infrastructure | 1.0 | 1.0 | 0.8 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 |

*Comments:* a) Fraction of recycled materials during recycling process; b) Includes exported fraction; c) n-fold change recycling of wood wastes is nowadays around 25% and of plastics near 16% (Mantau, 2012a; Consultic, 2013), respectively. A strong potential for material recycling of wood and plastics wastes is possible.

Currently, an interest in using wood and plastic post-consumer waste for energy purposes as for material purposes has been identified (Mantau, 2012a; Consultic, 2009; Consultic, 2011; Consultic, 2013). In the case of plastics, on one side, the energy content of plastics products is very high and can replace the use of new additional crude oil or other fossil fuel derivatives for energy purposes (Martens, 2011b). Plastics then become energy carriers after a material in-use lifetime. On the other side, the recycling of plastics require a very high selection process and minor polymer contamination or crossing, as a matrix cross-contamination can change the polymer physicochemical properties significantly and loose its economic value (Kozlowski, 2006; Martens, 2011d). For woods, a significant volume of post-consumer wood waste is under the class III or IV as they contain flame retardants and other hazardous substances, which are restricted for material uses and nearly 80% is used for energy purposes (Deilmann et al., 2014).

However, the possibility of saving or reducing resources and energy consumption for the manufacturing of new virgin polymer resins with mechanical or feedstock recycling must be contemplated (Kozlowski, 2006). Further, alternatives for methyl bromides, like physical wood treatments (heat in controlled atmospheres, irradiation, and so on) and other chemical substances such as sulfuryl-flouride, phosphine, and the like, have been suggested to fit European regulatory requirements (Banks, 2001) and could rise the volumes of post-consumer wood wastes suitable for material uses. It is, therefore, important to evaluate a scenario where the potential of recycling for plastics and wood is expanded and very high levels of recycling are reached. This scenario evaluates an escalation in the recycling rates of the carbon-based materials *ceteris paribus*. By 2055 the recycling rates for the material groups are assumed to reach 95% for paper, which means an increase of 6% compared to final value in the baseline scenario. Wood recycling is assumed to reach 42% of the recovered wastes and for plastics a recycling rate of 32% is considered meaning for both materials 18% above the values of the baseline scenario. These values were chosen to create a significant and very optimistic improvement of current levels under possible and better technological and recollection processes.

### 5.5.2. Scenario "Reuse"

At an anthropogenic level, the influence of changes in consumption patterns, voluntary or forced, gives an insight of the impact of human consumption behavior in AMS. Consumption patterns can be expressed in terms of reuse or refuse of final goods. Reuse implies the reutilization, share or exchange of a product for the same service or for a new one, represented in the AMS as an extension of the product in-use lifetime. This is known nowadays, among other expressions, as collaborative consumption patterns with potential development inside the economy and society (Leismann et al., 2012).

The scenario "Reuse" will investigate *ceteris paribus* the effects and impacts along the AMS (in terms of raw material requirements, production volumes, stock dynamics, post-consumer waste generation and carbon-related emissions) caused after varying in-use lifetimes of consumer and capital goods both at an individual and societal level. Consumption patterns of services are rated with the value of one (1.0) in the baseline scenario, indicating no changes in the average in-use lifetime of the service (see the line "Service-based lifetime change" in table

9). Collaborative consumption patterns have higher values than 1.0 describing a reuse pattern with the proportional change in the in-use lifetime. Table A.2 in Annex A exhibits the assumed changes in consumption patterns in terms of services and material groups for this scenario.

Short-lifetime consumer goods are concentrated on the packaging sector and, all in all, paper products. The fragility and instability of this material is not a guarantee for a comprehensive extension of the in-use lifetime. On the other side, middle and long in-use consumer goods are composed of wood and plastic products, mostly used for well-being services, specially furniture for housing and offices and household elements, or final goods with plastic components like automotive and other transport vehicles. These products are much more durable and its use can assumed to last longer. Therefore, the reuse of goods considers short in-use lifetime goods could have an increment of 20% of the average in-use lifetime, while middle and long in-use lifetime products can reach higher stakes. However, for a sober and realistic behavior of consumers, where reused products and the intention of using good longer is not voluntarily strong, it is assumed a reuse of products to extend its in-use lifetime in the order of ±20% for all goods (short, middle and long in-use lifetime groups). Changes in the consumption patterns of consumer goods have inversely proportional behavior: a reuse pattern (increment in the in-use lifetime) reduces the domestic per capita consumption of these final good. This means reusing a good will delay the need for obtaining a new one reducing the annual domestic per capita consumption for this final new product, as the change of behavior forces a change in the production volumes, which is then reflected on an inevitable change in the demand.

However, for capital goods it is assumed that no increase in the domestic per capita consumption takes place. The population dynamics describe an expected shrinkage of between 10 to 14% by 2055 attaining 67 to 72 million inhabitants (see figure 17 in chapter 4). This suggests the formation of obsolete stock as many residences will remain empty. An aggressive option of urban mining and exploitation of anthropogenic resources from abandoned constructions for the SRM recovery implies first an upturn in the demolition rate (or in other words a shortening of its expected in-use lifetime). Thus, a stronger tendency of demolition activities of residential and non-residential constructions and deceleration rate phenomenon of new built environments in Germany is assumed (Deilmann et al., 2014). Thus, the in-use lifetime of built environment is assumed to be reduced by 20% following the decrease rates of population by 2055 and the reductions in expansion-related inputs in residential buildings and infrastructure in Europe (Wiedenhofer et al., 2015). This means a reduction on average of the in-use lifetime of 9.1 years for dwellings and non-residential buildings. As most of the well-being service is composed of furniture and further household items these products are also affected by this decline.

Since no further constructions are required, the market shares of materials for residential buildings are also affected. With the deceleration in the construction dynamics, the market share of capital goods changes from 30.1% to 21.1% in wood products and 22.6% to 13.5% in plastic products. As a consequence, the market shares of consumer goods increment for example in packaging from 8.6% to 9.5% in wood products and from 33.3% to 36.7% in plastic products. The complete results are found in table A.7 in Annex A. Considering the assumed changes in the products' in-use lifetime and in the services' market share, the annual per capita consumption of final goods is estimated for the period between 2015 and 2055. The consumption reduces from 279.1 kg/cap to 233.1 kg/cap for paper products, from 532.9 kg/cap to 517.9 kg/cap for wood products, and from 203.1 kg/cap to 168.5 kg/cap for plastic products in 2055.

### 5.5.3. Scenario "Refuse"

The optimistic perspective of a positive behavioral change in the consumption patterns is just one side of the medal. The reuse of goods might not be fully coherent with the future consumption patterns of consumer goods and on the contrary an increase in the consumption within a "throw-away" society might happen. In fact, the German consumer spending of goods and services has increased by 17% between 1991 and 2008 (Leismann et al., 2012). These types of actions create a burden at the resource demands and environmental level, and are key factors for understanding the dynamics of the AMS under the perspective of a circular economy. Therefore, the impact of a change in the consumption patterns, in terms of refuse, should be examined.

The scenario "Refuse" contrary to the scenario "Reuse" assumes a reduction in the in-use lifetime of all services and products in an equivalent fashion to the Reuse scenario. These cutbacks will reflect in increments of per capita consumption of consumer goods as the volumes of goods are more frequently discarded and more products are required per year. In the model, it represents values lower than 1.0 for the consumer goods. The capital stock remains the same as in the scenario "Reuse" as it was noted above the decoupled effects of consumer behavior between consumer and capital goods. The domestic per capita consumption for final goods increments from 279.1 kg/cap to 334.6 kg/cap for paper products, from 532.9 kg/cap to 559.3 kg/cap for wood products, and from 203.1 kg/cap to 239.4 kg/cap for plastic products in 2055.

### 5.5.4. Scenario "Circularity"

A best-case scenario should combine the conditions of a good recycling strategy and environmental-friendly consumer behaviors in order to envisage the limits of circularity within an AMS. The scenario "Circularity" provides a directive in the path for understanding the sustainable development of the carbon-based material industries in Germany. In this scenario the recycling rates of paper, wood and plastics post-consumer wastes are boosted and attain potential maximum realistic material turnover reaching on average 95% for paper, 42% for wood and 32% for plastic post-consumer wastes, after assuming an improvement in the collection and sorting technologies. This in combination with a consumer behavior based on the collaborative consumption principles describes an optimum from an AMS perspective of the best option for improving circularity. To complement these assumptions, a technological innovation in manufacturing processes is considered leading to a reduction of the material losses after achieving very high manufacturing efficiencies. Thus, from the current manufacturing efficiencies described in table A.3 in Annex A, paper increases from 82% to 90% and wood and plastic achieve a manufacturing efficiency of 95%. Further, recycling efficiencies reach all 95% assuming the recovery systems for recycling provide good sorting and quality, an eco-design policy for product recycling is introduced, which reduces the amount of lost material and hazardous chemicals in some products are substituted for more environmental-friendly substances allowing material use of these products. A reuse-oriented society for consumer goods is present using final goods between 10% and 20% longer. This represents an increase between 0.5 to one year for short-lifetime products and between 1.2 and 4.1 years for middle- and long-lifetime products.

Such scenario should target for a reduction of carbon-related emissions and protection of the natural and anthropogenic resources, but it can be quite unrealistic or not attainable in the coming years. However, knowing the current technological and industrial context for ideal waste management processes, it is important to visualize the potentials for improvement for the carbon-based materials along the AMS.

### 5.5.5. Scenario "Substitution Plastic"

Polymers and plastics are considered materials of the future delivering a high diversity of combinations and applications (Nieber, 2014). Such versatility opens new markets and offers technical advantages with new high-tech functions using carbon in polymer or wood-plastic composites (Ashori, 2008; Cote et al., 2009), in nanotechnology (Möller et al., 2013), or in organic photovoltaics (Sekine et al., 2014), among others. Further, the use of plastics in automotive use as measures for increasing vehicle performance and reduction of fuel consumption is taking place (Kozlowski, 2006). Parallel to this increment in plastic use, a growth of wood volumes used for energy purposes is also perceived (Mantau et al., 2010b). Additionally, the low price of oil, although expected to increase, is believed to remain below the 90 U.S. dollars barrier in the coming years (Smith, 2015). This still maintains a cost-efficient position for the plastic industry.

Material substitution takes place when a product with specific raw material composition is replaced with another product that fulfills the required needs with another raw material composition. In these group of scenarios product substitution takes place with the aim of measuring the impact of non-renewable sources upon environmental or resource burdens. Paper and plastics satisfy common services, like packaging or communication. Wood and plastics similarly provides services of construction, packaging and indoor applications (furniture or households items). Thus, plastics have the potential to replace both wood and paper in several product groups and services (Dispan, 2013a; Vassiliadis, 2014). Plastics, contrary to wood and paper, come from non-renewable origin and its carbon emissions are definitely not neutral contributing in the long run to the human-induced climate change. Further, the low biodegradability of plastics cause environmental impacts especially in sinks, like the oceans, such as marine littering (Schulz et al., 2015). Finally, the current low price of oil might trigger the consumption of plastics to a higher substitution of services. The use of plastics is increasing and a substitution phenomenon is occurring both worldwide and in Germany (Dispan, 2013a). A substitution potential of services provided by paper products and wood products for plastic products is possible. Examples are the "plastic bag vs. paper bag" dilemma or the replacement of items in residential and non-residential buildings where larger use of plastics products (windows frames, flooring, insulation, furniture, among others) in these environments is seen (Vassiliadis, 2014).

In this scenario, a preference for plastics use over paper and wood is considered with effects in the market share. Thus, the domestic per capita consumption of plastic rises, while the consumption of paper and wood decreases. In this case, the per capita consumption for final goods reduces from 279.1 kg/cap to 219.1 kg/cap for paper products, from 532.9 kg/cap to 452.9 kg/cap for wood products, and increments in plastic products from 203.1 kg/cap to 343.1 kg/cap in 2055. To achieve this, it is assumed a reduction of 60 kg/cap of paper material and 80 kg/cap of wood material that are substituted for plastics along the different services. Moreover, the preference for plastic packaging over paper packaging doubles and in the transportation sector and indoor areas in constructions increases between 20% and 60%. In other words, plastic consumption increases domestically by 140 kg/cap. Considering this consumer pattern as a global phenomenon, foreign per capita consumption of plastic is also incremented by 30 kg/cap.

## 5.5.6. Scenario "Substitution Plastic +"

Under the current technological waste management structure, the dramatic upturn of plastic consumption can poses critical environmental problems both in material and emissions aspects. As a measure to cope with this burden the scenario "Substitution Plastic +" replicates the conditions of scenario "Substitution Plastic" however, with an improved recycling rate. In this case the same con- figuration of the scenario "Recycling" is used for the plastic materials. If such changes in the consumption choices occur, this scenario can identify the required surge of the plastic recycling rate to match at least the environmental burden of the baseline scenario.

## 5.5.7. Scenario "Foreign"

A higher foreign consumption per capita compared to the baseline scenario can alter significantly the AMS dynamics, increasing resource demand, putting higher pressure in the manufacturing sector and market trade. An increment in the foreign demand of carbon-based products is studied. Here, it is assumed a stronger boost in the foreign demand of paper, wood and plastic products, as developing countries have stronger economies and its population are larger and with higher purchasing power capacity. However, the frequently used dynamic modeling criteria, where the current annual growth rates are for developing countries are assumed to match final consumption levels of developed countries, is avoided. Such assumptions are perverse as such goals will indicate an extremely fast growth rate causing an overuse and swift depletion of natural resources worldwide.

Therefore, the foreign per capita consumption in 2055 is assumed to meet comparable volumes of current levels the average per capita consumption of the material groups in the European area (FÖP and Ökopol, 2013; Mantau et al., 2010b; TECPOL, 2008). In this sense, while domestic demand maintains the baseline scenario dynamics, the foreign level paper products grow at an annual rate of 2.1% to attain 147.0 kg/cap in 2055 (over 56% of the baseline scenario values with 91.7 kg/cap). Wood products expands by 1.3% per year to hit 478 kg/cap and plastics increase 0.57% faster annually than the baseline scenario to reach 136 kg/cap in 2055. Recalling the discrepancy between the reported data for foreign per capita consumption, this scenario offers the possibility of observing of the effects a growing consumption in all materials.

# 5.6. The German carbon-based AMS according to alternative scenarios

## 5.6.1. Raw material requirements

In figures 42-A to 42-F the total (TRM) and secondary raw materials (SRM) requirements per material group are presented for each of the scenarios. In figure 42-A the TRM requirements for the manufacturing of paper products are shown. The total requirements have constant increasing dynamics along the scenarios. A parallel growth behavior is observed between the scenarios with the exception of the Foreign scenario[6] and the Substitution group scenarios (these are the scenarios "Substitution Plastic" and scenario "Substitution Plastic +"). In the

[6] For easiness in the text reading a capitalized adjectival derivative form of the alternative scenario names is used.

Foreign scenario a drastic TRM expansion has a continuous growth reaching 61.1 Mt in 2055. This is an upturn of 47% compared to the baseline scenario that has a final total material requirement of 41.7 Mt. The Refuse scenario also presents a higher use of total raw materials, with a growth rate similar to the baseline scenario and comes to 47.0 Mt in the last year of the simulation. The Refuse scenario however, suffers a dramatic development in the raw material demand with an average additional volume of 4 Mt annually compared to the baseline scenario. The Reuse and Circularity scenario improves the required volumes with a reduction of the total annual raw materials requirements with 2 Mt and 4 Mt, respectively. A different dynamic is recognized in the Substitution group scenarios as the reduction in the demand for raw materials for paper products reaches 13% in 2055, but with a better performance from the baseline scenario. The Recycling scenario experiences no changes at all.

The SRM dynamics in figure 42-B describe the development for paper products. With a very akin development pattern as the one seen in TRM, the Recycling and Refuse scenarios provides the largest volumes in 2055 with around 17.5 Mt. Nevertheless, the Recycling scenario has an increasing dynamic, while the Refuse scenario maintains a constant supply of SRM of a similar volume. As a response to the lower TRM requirements, the Circularity, Reuse and Substitution group scenarios supply a lower SRM volume as the Baseline scenario. Because of the high paper recovery rate in all scenarios the volumes of recovered paper are stagnated, and just a slight improvement can be seen in the Recycling scenario. In figures 42-A and 42-B it is seen that the Circularity and Behavior scenario reduces the raw material requirements, while the Refuse scenario boosts the demand of these resources.

Similar responses are seen in the wood and plastic raw materials demand. Figure 42-C illustrates the dynamics for wood raw materials. A reduction in the TRM in all scenarios is distinguished apart from the Foreign scenario, which maintains a linear growth to hit 31.2 Mt in 2055. The Refuse, Reuse and Circularity scenarios present a rapid reduction in the TRM wood requirements until around 2040 with 20 to 25% lower demands than the Baseline scenario. Afterwards the demand rises again to attain, for instance, in the Refuse scenario likely levels form the Baseline scenario. The SRM in figure 42-D remain very close to the baseline scenario volumes. The Recycling and Circularity scenarios present similar dynamics until nearly 2035, when the latter stagnates with an average supply volume of 6.4 Mt. The Recycling scenario continues to rises with a linear development until 8.0 Mt in 2055. Now, the dynamics of raw materials for plastics in figure 42-E have clear growing trends. The Reuse and Circularity scenarios will grow at a comparable dynamic as the Baseline scenario; however, the TRM requirements for both scenarios will be on average 3.1 Mt lower per year, representing a reduction between 12%-16% along the periods. On the other hand, the TRM in the Substitution group scenarios is clearly defined and raises dramatically 15 Mt above the baseline scenario by 2055. A similar behavior is observed in the SRM dynamics in figure 42-F, all with increasing patterns. A larger volume of SRM is obtained with the Substitution scenarios without and with improved recycling rates (5.3 Mt and 9.4 Mt in 2055, respectively) and the Recycling scenario with 6.1 Mt in the final simulation year. These volumes cover at most 20% of the TRM requirements.

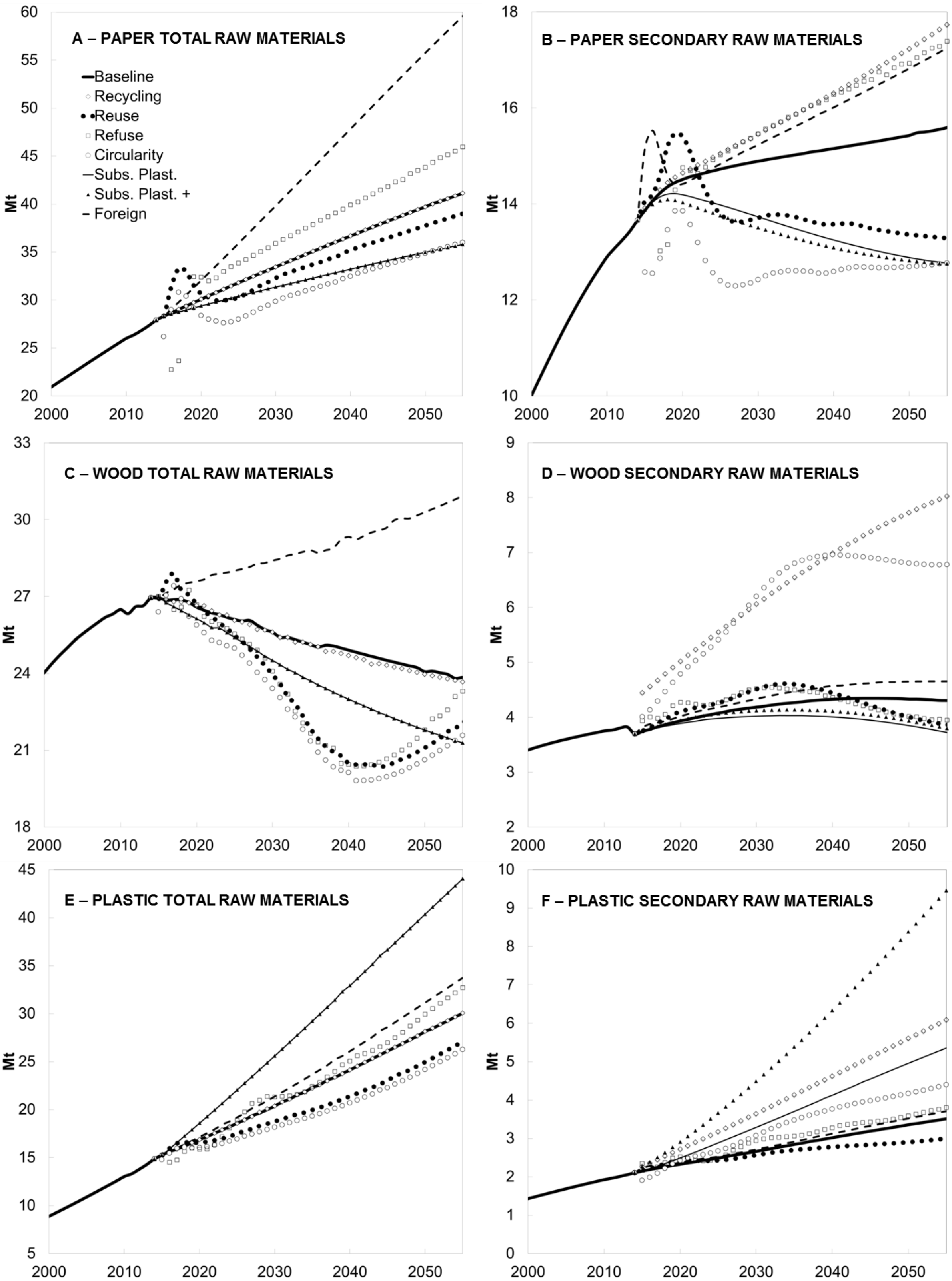


Figure 42: Scenario results of required total and secondary raw materials per material group.

## 5.6.2. Total production and foreign trade

Figures 43-A to 43-D illustrate the total production volumes and for each material group according to the different scenarios. In seven of the eight scenarios the total production volumes exhibit akin growing rates with variations between 76.1 Mt to 90.3 Mt in the year 2055; the exception is the Foreign scenario with a much rapid growth dynamic and achieves a final production volume of 109.7 Mt.

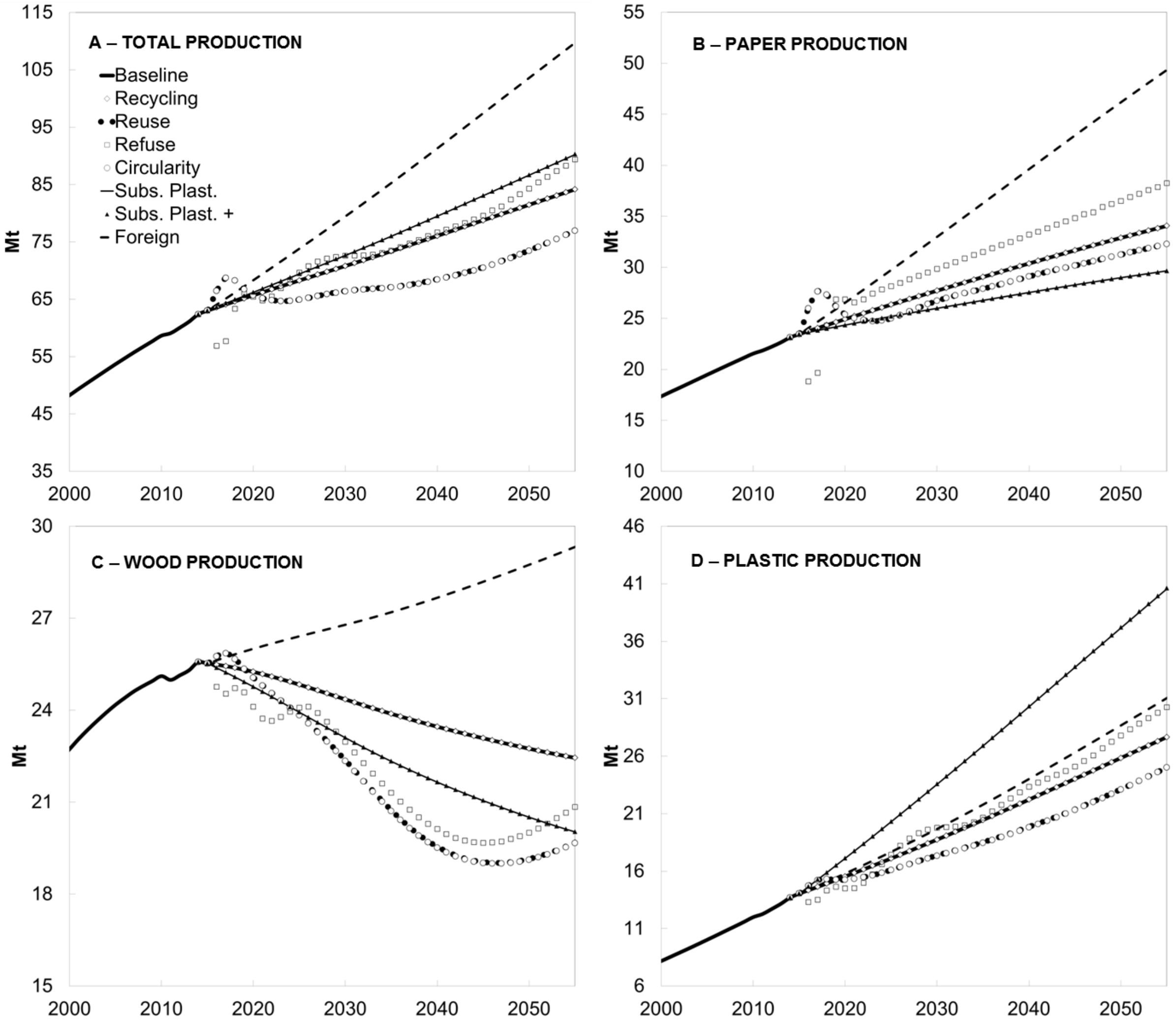


Figure 43: Scenario results of total production from carbon-based materials, Mt

An analogous pattern is repeated in the production volumes for paper final goods as seen in figure 43-B. Here, the Foreign and Refuse scenarios have clearly larger production volumes, while the Substitution scenarios experience the slowest growth dynamics reaching 29.9 Mt in 2055 or an increase of just 28% in comparison to 2014. The Baseline scenario experiences an increment of 47% for the same period. The Reuse and Circularity scenarios present an almost identical dynamic in terms of production, while the Recycling scenario and the Baseline scenario have the exactly same behavior.

In figure 43-C all scenarios estimate a downturn in the production volumes of wood reaching levels below the 2014 production volume (25.5 Mt) with the exception of the foreign scenario, that maintains a growing dynamic with final volume of 29.3 Mt. Two main dynamics are perceived in the production of wood final goods. The scenarios with no changes in consumption patterns present a very linear development along the simulation with growing trends for the Foreign scenario and shrinking volumes for the Substitution scenarios. On the other side, the scenarios including consumer behavioral changes (reuse or refuse of final goods at the consumption sector) present a non-linear dynamic. These latter scenarios, reduces significantly the production volumes during a certain period finding their lowest between 2040 and 2045. Afterwards, the wood production begins to develop still coming to year 2055 below the baseline production volumes.

Furthermore, in figure 43-D, the plastic production volumes all present increasing dynamics with very similar growth rates. The Reuse and Circularity scenarios, once again, present lower production volumes than the Baseline scenario. The remaining scenarios show a growth in the production volumes. It is evident, the dramatic change in the production volumes of the Substitution scenarios triplicating the production of 2014.

### 5.6.3. Domestic consumption

Figures 44-A to 44-D describe the domestic demand from the evaluated carbon-based materials. Several defined developments are observed in all three carbon-based materials. In figure 44-A the Reuse and Circularity scenarios display the lowest volumes in domestic demand reaching a lowest of 59.8 Mt in 2044. The Refuse scenario shows the highest consumption volumes reaching 81.6 Mt in 2055 after a dramatic increase in the demand from 2030 on. The rest of the scenarios kept a very similar dynamic compared to the baseline scenario.

The domestic demand for each of the three carbon-based materials has independent behavior. In the Refuse scenario, the domestic demand for paper products described in figure 44-B have a notorious increment following the past growing rates reaching 26.1 Mt in 2055. It is observed in the Reuse, Circularity and Substitution scenarios a reduction in the domestic demand meeting in 2055 consumption levels equivalent to 1990 with 15.1 Mt. The Recycling scenario keeps the same trend described by the Baseline scenario. The domestic demand of wood product present a different behavior as seen in figure 44-C. The Substitution scenarios clearly have a lower consumption of wood showing a continuous cutback until 2055. The three behavior-related scenarios present similar dynamics with an initial downturn and a final recovery of the domestic demand after 2030 to reach wood demands between 35.2 Mt and 38.1 Mt in 2055. The remaining scenarios do not show any significant difference in comparison to the Baseline scenario. Finally, the domestic demand for plastic goods shown in figure 44-D describes the dramatic increase of plastic demand in the Substitution scenarios to 23.9 Mt in 2055. The Refuse scenario presents slight growth in the demand reaching a maximum of 16.8 Mt. The Circularity and Reuse scenario have the lowest domestic demand at a near value of 11.3 Mt.

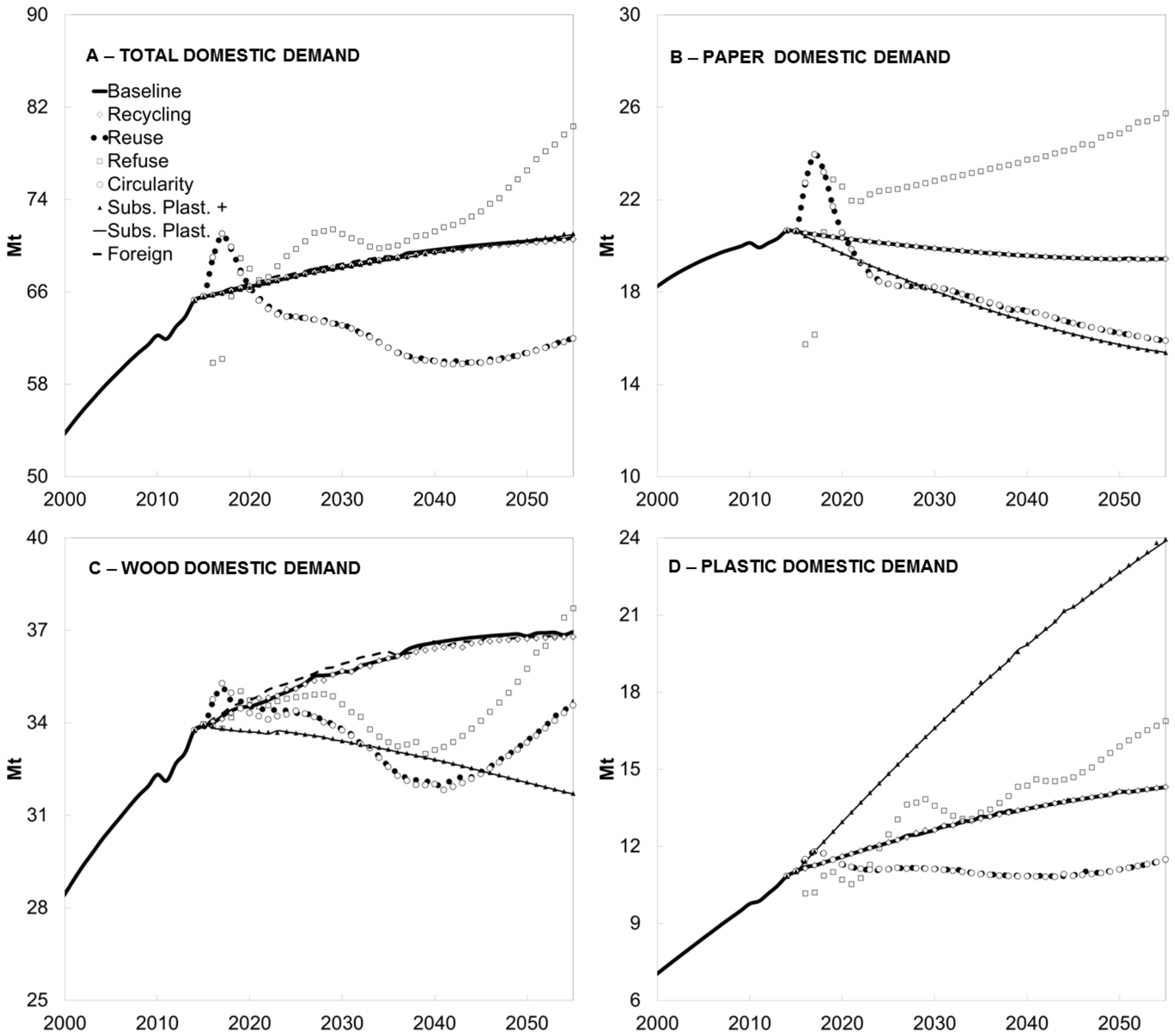


Figure 44: Scenario results of domestic demand from carbon-based materials, Mt

## 5.6.4. Stock dynamics

In figures 45-A to 45-D the stock dynamics of the carbon-based materials are presented. Three main dynamics are grasped between the scenarios in figure 45-A. The Reuse and Circularity scenarios, despite the short increase in the stocks between 2015 and 2020, peaking in 2022, present a drastic downturn achieving lower stocks than in year 2000 by 2055. A second dynamic is seen with the Refuse scenario where carbon stocks fluctuate between 420 and 450 Mt with no clear decreasing trend. Nevertheless, it builds larger stocks than the other consumer-related scenarios after 2030. The last clear tendency is conformed by the Foreign, Substitutions group and Recycling scenarios. These follow a very similar development compared to the Baseline scenario, where stocks are built up and peak between 2035 and 2045 and remain around 470 Mt. In figure 45-B paper stocks dynamics all present a lessening in the stocks dynamics, besides the Refuse scenario and in lesser degree the Foreign scenario. The dramatic boost in paper stocks observed in the Refuse scenario in figure 45-B hits 102.5 Mt in 2055. The other scenarios remain in close range around 20 to 30 Mt in year 2055; nevertheless with lower stocks than in 2014. Figure 45-C displays the stock dynamics from wood products. Comparable developments between the Reuse and Circularity scenarios are observed, with a staggering drop to 195 Mt attaining 1990 stock levels by 2055. The Substitution scenarios also present a notorious decrease with a slower dynamic attaining a mid-value of around 285 Mt in 2055 between the baseline scenario (346 Mt) and the Circularity scenario (195 Mt). Figure 45-D illustrates also three noticeable trends.

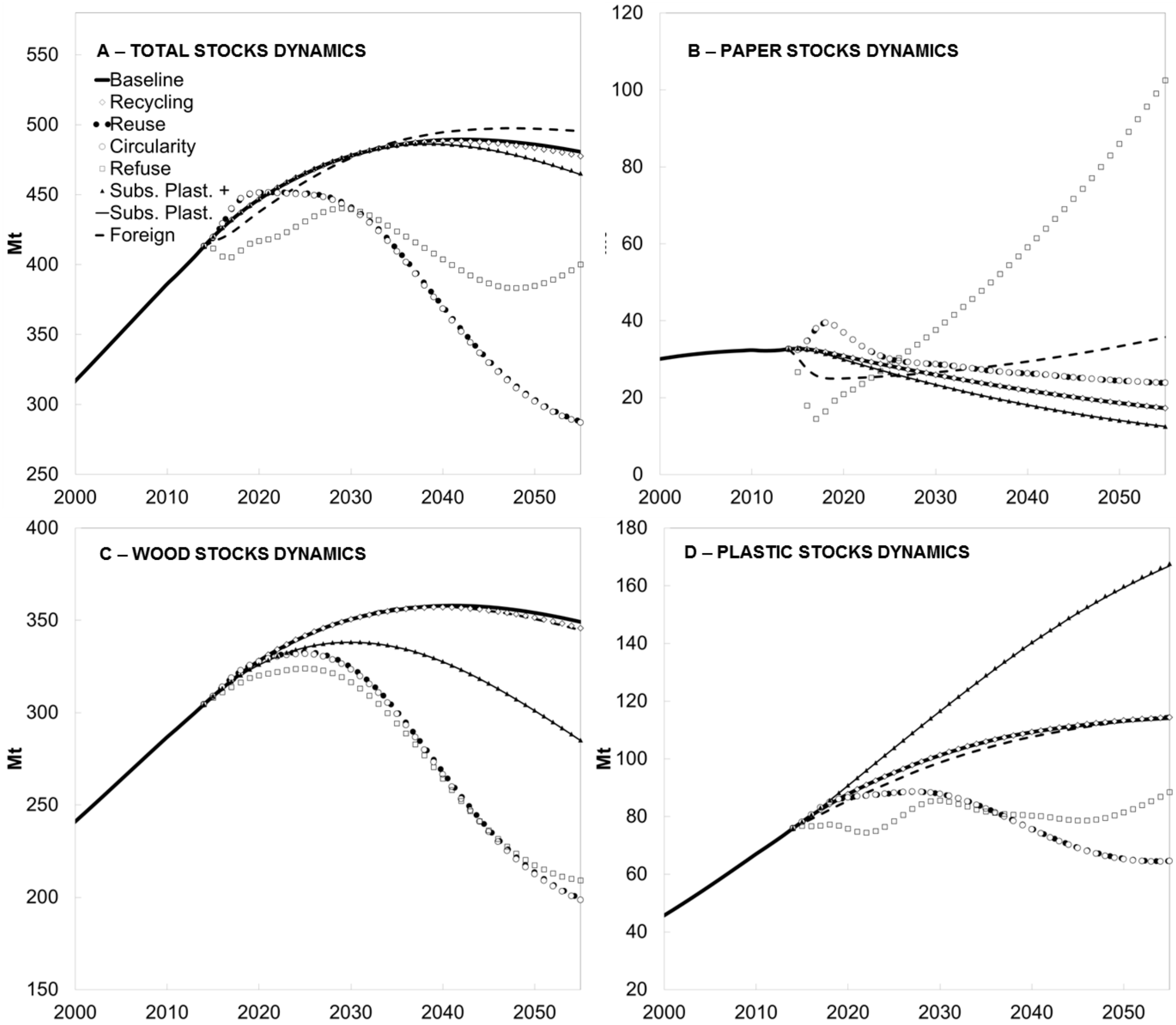


Figure 45: Scenario results of stocks dynamics from carbon-based materials, Mt

The largest stock comes from the Substitution group scenarios, where a final stock of 167 Mt is achieved in 2055 showing no signs of deceleration. Low plastic stocks are found in the Refuse, Reuse and Circularity scenarios with final volumes of 88 Mt and the last two with 64 Mt, respectively. The Reuse and Circularity scenarios present an increase in the stock dynamics peaking in 2025, while the Refuse scenario oscillates and describes a very slow growth, crossing the stocks volumes of the former scenarios by 2036. A comparable behavior is seen, in the paper stocks dynamics (figure 45-B) in 2025 and with lesser degree, in the wood stocks dynamics (figure 45-C) by 2043.

### 5.6.5. Post-consumer waste

Figures 46-A to 46-D describes the total post-consumer waste volumes per material groups. In figure 46-A the total post-consumer wastes per scenario are illustrated. The Refuse scenario displays a higher waste volume reaching 54.8 Mt in 2041 obtaining 8.9% more wastes compared to the scenario. In the same year the Reuse and Circularity scenarios reduce the total waste volume by 3.7% in a decreasing trend to reach 43.3 Mt of wastes, an equivalent volume to the amounts of wastes generated in 2014.

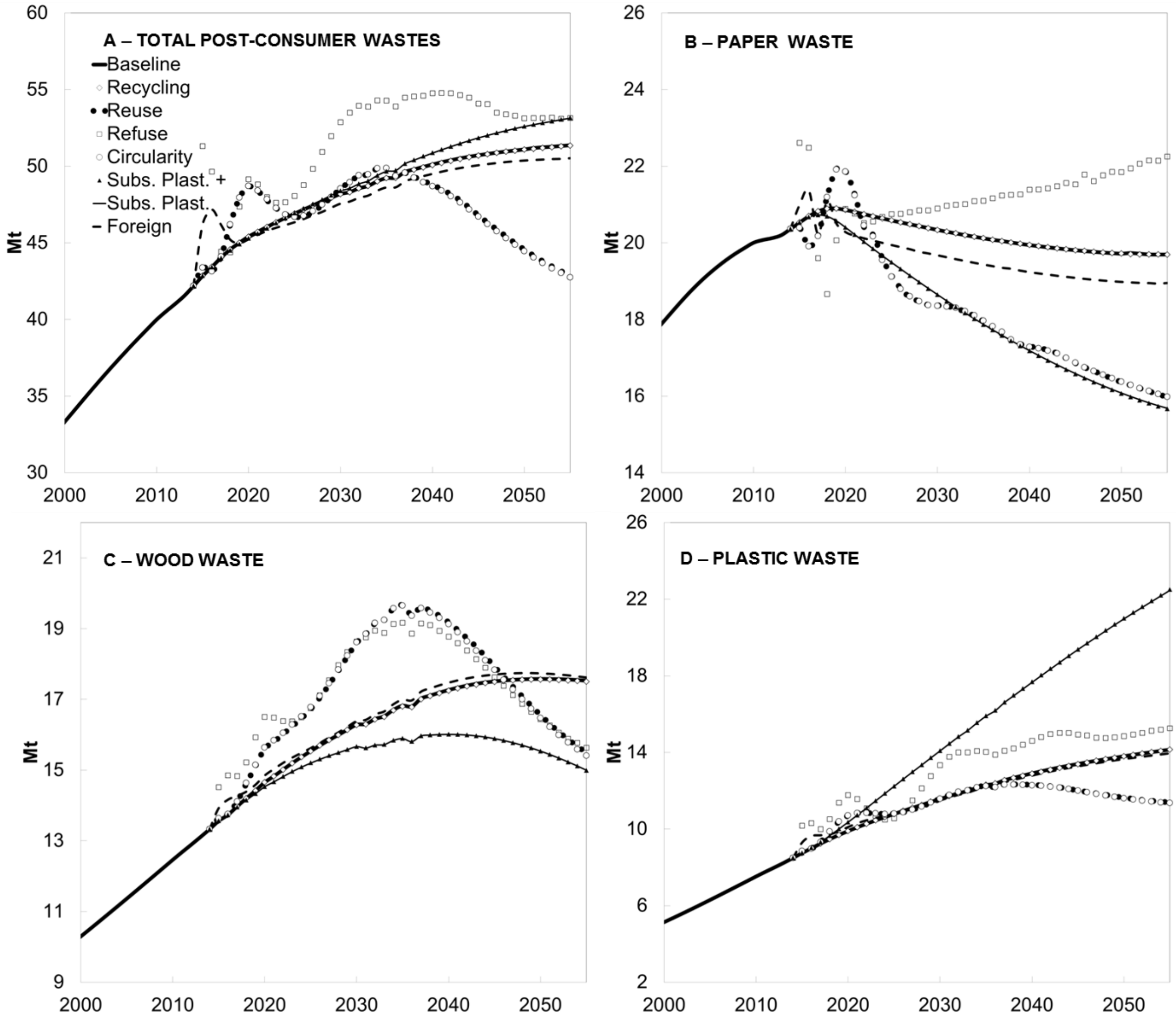


Figure 46: Scenario results of total post-consumer waste volumes from carbon-based materials, Mt

The other scenarios maintain a similar trend compared to the Baseline scenario producing between 50.4 Mt and 53.1 Mt in 2055. In figure 46-B it is observed a growing trend in the Refuse scenario being the only scenario with a continuous increase in the paper waste outflow, with 2.7 Mt more in 2055 that the baseline scenario. Contrarily, the Reuse and Circularity and both Substitution scenarios have a noticeable and comparable lessening in paper wastes volumes, reaching early 1990s waste volumes between 15 and 16 Mt. Further the Recycling scenario shows no difference compared to the Baseline scenario. Figure 46-C displays three main developments of wood waste dynamics. The consumption-related scenarios (Reuse, Refuse and Circularity scenarios) experience a steep growth in wastes peaking in 2037, followed by a rapid cutback to attain lower levels than the Baseline scenario by 2.1 Mt. Both Substitution scenarios cut down waste volumes after peaking in 2035 reaching 14.9 Mt in 2055. The Recycling and Foreign scenarios follow very similar paths compared to the Baseline scenario levelling-off at 17.4 Mt of wood waste in 2055. Figure 46-D clearly demonstrates the effects of a substitution effect, with an increment in plastic wastes in both Substitution scenarios reaching 23.1 Mt in 2055. On the contrary, a reduction in the post-consumer waste is observed in the Reuse and Circularity scenarios reaching 10.1 Mt in 2055.

### 5.6.6. Carbon-related emissions

The development of carbon-related emissions from carbon-based products are presented in figures 47-A to 47-D. Carbon emissions are quantified in Mt $CO_2$-eq. Figure 47-A illustrates total and varying carbon-related emissions from the different scenarios. The Recycling and Circularity scenarios present the lowest emissions. The Recycling scenario presents a very stable dynamic maintaining current emission levels and reaching 91.1 Mt $CO_2$-eq in 2055. The Circularity scenario also describes a very slow dynamic with a noticeable decrease after 2037 where the emissions at 94.7 Mt $CO_2$-eq become lower than the Recycling scenario. The Circularity scenario cuts its emissions to 81.5 Mt $CO_2$-eq in 2055. The Reuse scenario shows a similar pattern to the latter scenario described, but shifted to the high with approximately 10 Mt $CO_2$-eq annually. It presents an increment in the carbon emission until 2037 and then shrinks to meet emissions volumes lower than the Baseline scenario volumes by 2055. The Reuse scenario achieves carbon emissions in 2055 comparable to current ones.

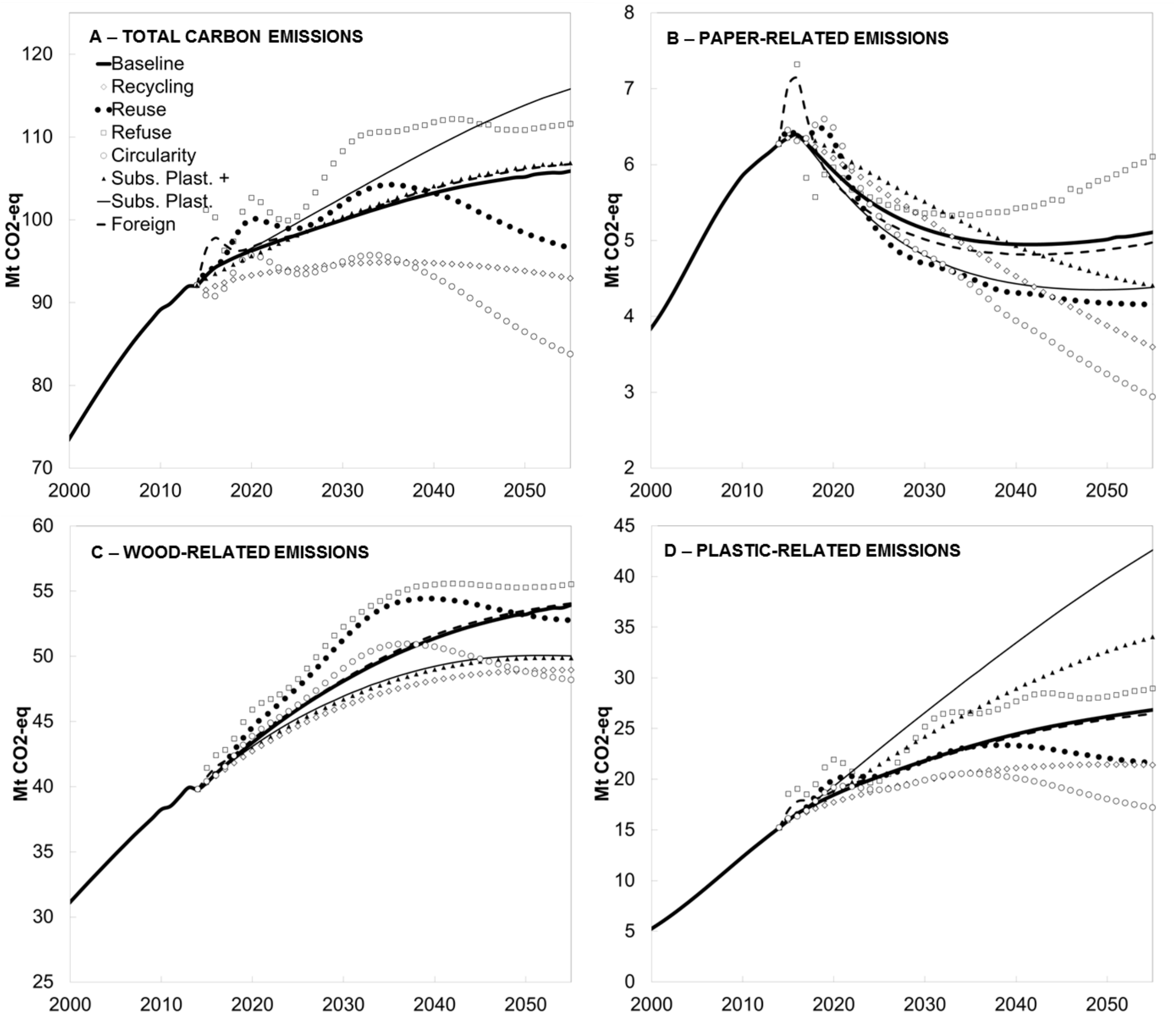


Figure 47: Scenario results of carbon emissions from carbon-based materials, Mt $CO_2$-eq

Some scenarios presented higher volumes in carbon emissions than the baseline scenario. The Refuse and the Substitution scenario produced between 5% and 10% more carbon emissions with final volumes in 2055 of 109.9 Mt $CO_2$-eq and 114.5 Mt $CO_2$-eq, respectively. The Foreign and Substitution plus (+) scenarios described a very similar development compared to the Baseline scenario.

Paper-related carbon emission shown in figure 47-B will definitively reduce in the coming decades, with the exception of the Refuse scenario that after an initial cutback increases to 6.1 Mt $CO_2$-eq in 2055 equivalent volume to the current emissions coming from paper products. The Recycling and Circularity scenarios display the best reduction potentials achieving levels of 1998 (3.6 Mt $CO_2$-eq) and 1957 (2.8 Mt $CO_2$-eq), respectively by 2055. The rest of scenarios, with the exception of the Refuse scenario, present shrinkage in the emitted volumes compared to the Baseline scenario. Figure 47-C illustrates the wood-related carbon emissions. The growing developments of the carbon emissions show slight differences between the scenarios. Thus, it can be seen that the different scenarios settings do not affect significantly the wood-related carbon emissions. The Refuse scenario has a quick dynamic until 2035 where it stagnates around 55 Mt $CO_2$-eq. An equivalent dynamic is observed in the Circularity scenario however the carbon emissions present a cutback after 2035 reaching the lowest emissions of all the scenarios in 2055 with 46.7 Mt $CO_2$-eq. Parallel to the continuous increment of the Baseline scenario, the Substitution group and Recycling scenarios present a smooth increase with signs of stagnation after 2040. Because of these slow dynamic the Recycling scenario cuts nearly 4.6 Mt $CO_2$-eq less than the baseline scenario emissions in 2055. The Circularity scenario shows the faster reduction rate after peaking in 2034 to obtain the lowest carbon emissions volumes in 2055.

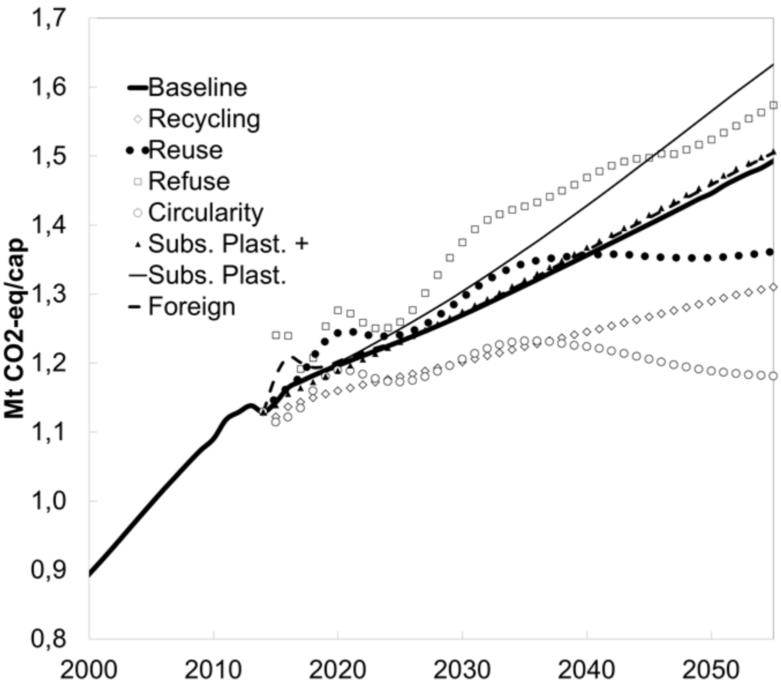


Figure 48: Scenario results of per capita carbon emissions from carbon-based materials, Mt $CO_2$-eq/cap

Further, figure 47-D displays a very particular behavior of plastic-related carbon emissions. These emissions do have a larger variability, with a tendency of having growing volumes in the coming years. Both Substitution scenarios (Substitution and Substitution plus (+)) have the largest carbon emissions with 42.6 Mt $CO_2$-eq and 34.0 Mt $CO_2$-eq, respectively. The

Refuse scenario follows these two scenarios with a volume of 28.9 Mt $CO_2$-eq. A reduction in the plastic emissions is observed in the Circularity, Reuse and Recycling scenarios. The two latter scenarios converge at around 21 Mt $CO_2$-eq in 2055, meaning a reduction of 25.5% compared to the Baseline scenario.

Finally, the per capita carbon emissions shown in figure 48 describe significant varied behaviors. Some present a continuous increase for the modeled period, while others achieve a cutback in the carbon emissions, reaching volumes below the Baseline scenario. By 2055 it will range between 1.18-1.63 Mt $CO_2$-eq/cap, with the Baseline scenario at 1.48 Mt $CO_2$-eq/cap. The Circularity scenario reaches the lowest carbon-related emissions in 2055 with 1.18 Mt $CO_2$-eq/cap meeting current emissions levels (1.12 Mt $CO_2$-eq/cap in 2014). On the other side, the Substitution scenario increases the per capita emissions by 10% compared to the baseline scenario, reaching 1.63 Mt $CO_2$-eq/cap in 2055. The positive outcome in cutting back emissions from the Recycling scenario in combination with a reuse pattern has notorious changes after 2035.

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# 6. Understanding the carbon-base AMS dynamics

## 6.1. Analyzing the results from baseline scenario

### 6.1.1. Raw materials requirements

The results obtained for the Baseline scenario in section 5.3 describes a consistent future and gives a possible development of the AMS in Germany. From figure 31, where the total, primary and secondary raw materials requirements and distribution are shown, the dynamics of raw materials shows a growth in the volumes of total required raw materials for paper and plastics products. The requirements for wood products appear to suffer a slight drawback maintaining current demand volumes. The transition of wood uses from material to energy purposes is reflected on the reduction of demanded volumes for material goods, in combination to the expected deceleration of new built environments caused by the declining German population in the coming decades. Nevertheless, the continuous increase in total raw materials for paper and plastic products is seen and it is mainly driven by the foreign demand.

The historic developments of total and secondary raw materials volumes for paper products have kept a proportional relationship. However, as the expected demands in foreign markets increases, this relationship changes dramatically and the total volumes of primary raw materials for paper becomes much larger than the amount of recovered secondary raw materials. This latter resource volume stagnates around 15 Mt per year along the simulation as illustrated in figure 31-C. In the case of raw materials for plastics goods, a continuous growth in both total and secondary raw materials is observed. Nevertheless, the needs of primary resources are also enlarged. Figures 31-D and 31-F reveal an increment in the primary raw material shares, as the use of recycled paper in Germany are almost saturated and the potential for increase of plastic secondary raw materials is limited by the preference for energy uses. Therefore, this potential gap should be covered with larger volumes of imported sources of primary or secondary raw materials. The possible development of resources for wood products shows a different behavior, with a reduction in the TRM and stagnation in the primary-to-secondary raw materials distribution as figure 31-E describes. Under such circumstances, the extraction or harvesting of PRM show no improvement compared to current states.

The primary-to-secondary raw material distribution for each of the material groups give a hint of the potentiality (or underdevelopment) of the recycling technologies deployment and capacity for these materials as illustrated in figures 31-D, 31-E and 31-F. These fractions in secondary raw materials are also driven by the growing foreign demand and the small recovery rates of wood and plastics post-consumer wastes for recycling. The increasing interest of using post-consumer plastic waste for energy purposes (Dispan, 2013a) as a mitigation measure to reduce use of primary sources like oil or coal for satisfying energy needs is taking place. This practice still has a greater impact in carbon emissions since plastics are non-renewable materials. The low secondary raw material fractions from wood and plastic is also a result of considering the total share of raw materials including imported primary raw materials, which also occurs with paper products but in a lower extent. Even further, this explains for instance why the secondary ratio of paper is not similar to the recovery rates of the waste management (VDP, 2013b). The recovered paper rate in 2013 was

71%, but the share in the total domestic demand of paper is just 56% (FÖP and Ökopol, 2013), which is very close to the value obtained from the model with 52%.

### 6.1.2. Total production and foreign trade

The constant increase in the manufacturing of paper and plastics products, shown in figure 32-A, is driven by the steep growth of exported goods and the parallel saturation of domestic demand attained by the expected population decline and the slow dynamic in the per capita consumption. In the case of paper products, Germany enjoys one of the highest per capita consumption in the world, with saturation signs as in the rest of European countries a reduction in the per capita consumption is identified (FÖP and Ökopol, 2013). Therefore, a dramatic slowdown in imported goods is observed. Plastic consumption still holds a growing gap. Nevertheless, these new demands might suggest a potential expansion or construction of production facilities within the country for the manufacturing of paper and plastic final goods, as the current state of production capacity is mostly covered. It should be denoted however, the current trends of opening new plastic manufacturing facilities in developing countries for the production of standard polymers as the labor costs are much lower (VCI and Prognos AG, 2013) and might provoke a challenging situation to attract new projects within Germany. The wood industry describes a different pattern. As discussed in section 4.3.2, Germany will continue to be a net wood importer (ETTF, 2011). The lower volumes of exported wood compared to the imported wood products as shown in figures 32-B and 32-C describes the limited availability, expansion and harvesting potentials of domestic forest resources. However, final goods for energy uses show an increase in the export of the total volume of wood products. Exports of paper and plastics will have a continuous growth, based on the demands of developing countries, which on average defines Germany as a net exporter of carbon-based material products as seen in figure 32-D. Notwithstanding, it should be mentioned that almost all Germany's raw materials for plastic production has foreign origin. In the near future it may have the need to import also chemical or mechanical pulp for the production of paper. Thus, in this case its net-export title of goods is also dependent on imported resources.

### 6.1.3. Domestic consumption

The apparent difference between the increase in the domestic consumption of wood in figure 33-A despite the perceived reduction in TRM requirements occurs first because the demand dynamics include the energy and non-energy purposes of wood as wood for energy satisfies one fundamental societal need. Second, the estimation of raw materials is focused only in domestic sources for material uses and not energy uses. This, to highlight the domestic raw material requirements for material uses as wood for energy has little relevance in a material stock-flow model. An important change in the consumption of paper goods is marked by the decrease of the service of communication as illustrated in figure 33-B. At the same time, a growing dynamic of plastics for communication as observed in figure 33-D evidences a partial material replacement for the same service. This is caused, among other factors, by the growing trends of electronic media use for publications and the transition of use of paper to special and technical applications (Dispan, 2013b). In this sense, as seen in figure 33-A, the total domestic demand of paper is kept at current levels even with the loss of market share in communication as new applications and specialized uses are being developed within the paper industry. This simultaneous switch in the demand in services alleviates partially the pressure of the paper industry in finding new paper markets. The declining trend of paper for communication calls for a strategy of the paper industry in finding new markets and development opportunities. This is being carried out, focusing on new applications for paper (Dispan, 2013b).

Further, the decreasing trend in the consumption of wood, as shown in figure 33-C, for residential, non-residential and well-being services, demonstrates the transition to energy uses in final wood products (not shown in the figure). The stagnation and subsequent decrease seen in capital goods is caused by the deceleration in construction of new built environments and replacement of construction materials; a phenomenon driven by the reduction of domestic population. The service of well-being has a prominent decrement and a very similar behavior to the residential and non-residential buildings, because most of this service corresponds to wood furniture and commodities for households and non-residential buildings. A different situation is seen with the well-being service in plastics in figure 33-D where no volume cutbacks are observed. The versatility and diversity of use of plastics in several well-being applications goes beyond the use of commodities and furniture. Therefore, the expected deceleration of the construction dynamics impacts partially this service. Further, the growing trends in the packaging service are seen in all three materials. Packaging of consumer goods is necessary and as both the domestic and foreign demand increases the need for packaging also grows. The plastic packaging shown in figure 33-D has the largest share but is still behind the use of paper for this service. Still the growing dynamics for plastic packaging are faster because of the permanent innovation and development of new polymeric matrices and functional uses for specialized products, as paper and wood are not able to fulfill these needs. Transportation also experiences a growing dynamic as the use of plastic parts in vehicles and automotive is expanding to improve operating performance and reduce fuel consumption.

### 6.1.4. Stocks dynamics

From figure 34-A, the decrease in the wood stocks build-up in 2040 reflects largely the delayed effect of the shrinking built environments and the expanding use and replacement for plastic in some products. This same pattern is repeated for the service of well-being in figure 35-B because most of these stocks are simultaneously used in dwellings and offices. A similar trend is seen with the paper stocks, while plastics are new and innovative material experiences a growth in its in-use stocks. Since almost 40% of the whole paper products palette are used for communication the effects of its share shrinkage is reflected on a dramatic reduction of its stocks as seen in figure 35-A.

The increase of plastics stocks has several reasons. First, the dramatic decrease in paper stocks for communications, as a response of the short in-use lifetime of these products and its low capacity for building stocks and shown in figure 34-B, is replaced by plastic goods. In this service, while paper stocks suffer shrinkage of 81% plastics stocks increase by 57%. There is no proportional equivalence in the amounts of material required for the service of communication. This evidences the advantage of the use of tablets or other electronic devices that are capable of saving large amounts of documents electronically. This represents a change in the communication channels with a lesser volume of materials. Further, the increase of plastic stocks in transportation as illustrated in figure 35-A do not signify larger stocks of automotive and vehicles for freight transportation in Germany. The increase of plastic stocks is the effect of a larger use of this material in this industry branch with the purpose of increasing performance and most important reduction of weight and economization of fuel. It is very likely that the transport service for the German automotive consumers will maintain a similar number of vehicles in stock per household and used for freight transportation. Assuming a relative constant stock of automotive and freight vehicles, nearly 330 kg plastics will be used on average per vehicle in 2055, compared to the circa 180 kg plastics per car used nowadays (Kozlowski, 2006). Further, same as the communication service for paper, the packaging service also has a decrease in its stocks caused mostly by the population change, as this service has a short in-use lifetime and no capacity to build stocks.

### 6.1.5. Post-consumer wastes

The total post-consumer waste and distribution in figures 36-A and 36-B shows a small reduction by 2040 caused by the decrease of sawnwood for material uses, with preference for energy uses. Thus, the effects of the increase of wood use for energy purposes are observed in the wood waste material flows of discarded goods. Further, the total flows of post-consumer paper waste do not decrease, as new application in special and technical uses arises. Plastic waste continues to increase its volumes as a response of material substitution in services like communication. In terms of services, the post-consumer waste indicates in general large shares of wastes from packaging, well-being and communication services. This occurs because these are mostly composed of short-life consumer goods with very high turnover rate and practically no stock building driven by an increasing per capita consumption. As illustrated in figure 37-A, in the case of paper the reduction of wastes from the communication service might intensify the import of recovered paper or even of primary fibers for the manufacturing of new goods, as the recovery of paper from special and technical application uses might have higher ratios of additives and fillers. Also, the increase in post-consumer waste in plastic for transportation is an effect of a more frequent use of plastics in automotive and freight vehicles.

The information from the post-consumer waste in terms of raw materials is an alternative and very crucial way of analyzing these flows, as they provide a guide to potential secondary raw material availability. The volumes presented in figure 38 are theoretical volume considering no material losses in the recollection phase. Problems such as waste sorting, contamination and losses must be considered. Unfortunately, the model is incapable of quantifying the real loss in materials for the three material groups. In general, an increase in the post-consumer waste ouflows volumes, especially in plastic products is expected, caused mainly by the growing applications of plastics in consumer and capital goods, and the substitution of wood for some products. Wood waste outflows have by far the largest carbon-based material waste distribution, but will face a slight stagnation in the last modeling decade (2040-2050) as the effects of the deceleration of new built environments is taken place.

### 6.1.6. Carbon-related emissions

The product-related emissions from wood and paper goods have a significant component of carbon neutrality as Germany's multi-purpose forest management seek for conservation and extension of forests for economic, environmental and social significance seen as sustainable management (Mann, 2012). The relative neutral forestry, according to EU-directives, shows that most of the wood and paper used in Germany is coming from sustainable forestry. This is not applicable to carbon emissions coming from plastic products which are a derivate from the oil industry. Plastic emissions are not neutral and contribute directly with the human-induced climate change. Even more, as seen in the upper left square in figure 39-A, plastics (white area) are gaining a larger share in the total carbon emissions in the coming years.

Comparing the emissions caused by the manufacturing processes that is the emissions for energy and heat requirement, which are not included in the model, it becomes clear that the contribution of carbon emissions from anthropogenic stocks rely on a significant order of magnitude. For example, 0.85 tons $CO_2$-eq are emitted in the production of one ton of paper (FÖP and Ökopol, 2013). In 2014, 23.11 Mt of paper were produced meaning 19.65 Mt $CO_2$-eq. The emissions from post-consumer paper waste in the same year were 6.29 Mt $CO_2$-eq representing 32.0% of the manufacturing emissions. In the case of plastics, these have a very high energy content at a low cost and are very attractive as secondary fuel or alternative fuel resource. The use of plastics for energy purposes might consider the substitution of primary non-renewable resources. However, considering the origin of plastics, emissions from plastic wastes, could be seen as delayed emissions of non-renewable resources. In this sense, no net positive effect of incineration of post-consumer plastic on climate change is found. The increase of use recyclates for material purposes guarantees the capture of carbon in the material, and should be considered as a serious mechanism for the use of plastics wastes.

## 6.2. Analyzing the results from alternative scenarios

In section 5.6 a thorough description of seven different alternative scenarios was presented. Some of the scenarios focused on specific changes in the system *ceteris paribus* while other combined changes in several variables. The Recycling scenario evaluated the effects of increments in recovery rates and recycling efficiencies of the carbon-based materials. Two scenarios focused on the impact of consumption, with the evaluation of shortening and extension of the in-use lifetime of final goods, the Reuse and Refuse scenarios, respectively. An additional scenario combined the configuration of the Recycling and the Reuse scenario named Circularity scenario. The expected increment in preference and use of plastics both at domestic and foreign level were evaluated in the Substitution scenario, which was complemented with a combined scenario Substitution plus (+) scenario where an improved recycling strategy of plastics was introduced. Finally, the Foreign scenario observed the effects of an increase in the foreign per capita consumption of all the evaluated carbon-based products. It must be stressfully denoted the plausibility of the scenarios in real contexts. Some scenarios can be seen as "intellectual games" with the purpose of evaluating the limits and behavior of the AMS. Nevertheless, the evaluation on each scenario of the AMS and each of the material group provided on first hand an overview of the multiple possible developments and contexts of the carbon-based material systems in the German anthroposphere and second the behavior of each material group under potential states along the different dynamic simulations.

### 6.2.1. Raw materials requirements

The developments of total and secondary raw materials in the different scenarios shown in figure 42 are driven by several factors. In the Reuse, Refuse and Circularity scenarios the non-linear dynamics occur as a response of the change in the in-use lifetime of products. In the Refuse scenario the shortening of the in-use lifetime of goods increases the per capita consumption of consumer goods. On the other hand, a reuse pattern in both Reuse and Circularity scenarios, provides a longer use of the goods and reduces the per capita consumption. For instance, a shortening of 20% in the in-use lifetime of consumer goods (refuse behavior) increases the per capita consumption of paper nearly 19%, of wood around 6% and plastics in 18% compared to the Baseline scenario. On the contrary, an increment of 20% (reuse behavior) in the in-use lifetime of consumer goods reduces the per capita consumption of paper and plastics in 16% and in wood the reduction is 1% using the Baseline scenario as reference. This indicates linearity with plastics and paper goods, leaving wood products aside. The extent of reuse or refuse is the proportional to the domestic per capita consumption, especially with the consumer goods. The low changes in wood products indicate the large use of wood in capital goods. The increase of secondary raw materials in the Recycling scenario for all materials is clear. In figure 42-B where flows for recovered paper are shown, similar volumes of secondary raw materials are obtained to the Refuse scenario without increasing domestic per capita consumption. This indicates the effectiveness and positive impact of recycling. An equivalent development is observed in figures 42-D for wood products until around 2040 were an abrupt change in the dynamics of the Circularity scenario takes place. In this scenario, the volumes of TRM attain the scenario-lowest volumes. Simultaneously, it reaches the highest SRM volumes from all the scenario results.

The reduction in TRM suggests the influence of consumption patterns in the total demand of raw materials, and shows the increasing demand for primary raw materials, as the volumes of secondary raw materials are saturated (in the case of paper) or are still very low (in the case of wood and plastics). Further, it illustrates that slight changes in the in-use lifetime of final goods, which in this case were less than 20% of its standard expected in-use lifetime, can have significant effects in the primary and secondary resources in the material systems.

Further, in this same scenario the wood consumption patterns change significantly the dynamics of the demand for total raw materials as a response of the large use of wood in capital stocks. Notwithstanding, the reduction of the in-use lifetime in capital stocks is happening as a response to the declining population. Thus, a drop in the total raw materials is seen. The final increase of TRM after 2042 that occurs in the Reuse, Refuse and Circularity scenarios, illustrated in figure 42-C, is caused by the decrease of wood stocks as the built environment shrinks but energy demands do not. The volumes of post-consumer wastes experience a significant decrease in the Refuse, Reuse and Circularity scenarios for the last decade and precipitates SRM availability as shown in figure 46-C. The continuous growing TRM dynamics for plastics in figure 42-E and SRM in figure 42-F indicates a permanent pressure in demand and supply for non-renewable resources. The high recycling rate of plastic in the Substitution plastic plus (+) of 32% is under current technological and recyclers interest an upper limit value. This indicates, still, the potential of SRM volumes that could be recovered from plastics for material uses.

### 6.2.2. Total production and foreign trade

In the Reuse and Circularity scenarios a reduction of the manufactured volumes compared to the baseline scenario is observed, as described in figure 43-A. Both scenarios show an almost identical dynamic. Thus, the effect of recycling of post-consumer wastes is minor as no restriction of primary raw materials supply was introduced in the model. This pattern is also seen in the dynamics of Recycling scenario that presents no difference with the baseline scenario. It is the long in-use lifetime of products what makes the domestic demand stable. In the Refuse scenario the manufacturing volumes per carbon-based material increment between 3 and 4 Mt annually as a response to the shortening of in-use lifetime of goods and the higher per capita consumption which increases the demand for raw materials. The shortening of the in-use lifetime in 20% increases the production requirements of paper and plastic between 12% and 20% as seen in figures 43-B and 43-D, and between 2% and 6% for wood products as shown in figure 43-C compared to the Reuse and Circularity scenarios. These differences highlight the effects of consumption patterns variations.

In figure 43-B a decrease in the production volumes of paper is seen in the Substitution scenarios. Reducing a consumption of 60kg paper/cap, that is 21% in comparison to the per capita consumption in the baseline scenario, signifies a total reduction of 13% in the paper production volumes. In other words, for every kg of paper less in the domestic per capita consumption it is expected a reduction of 0.5 Mt in production volumes, which is also reflected in a proportional reduction of the TRM requirements. In the same perspective, the wood products in figure 43-C had a reduction of 80 kg wood/capita, which corresponds to 14% less than the Baseline scenario values. This change has a reduction impact of 11% indicating a more favorable effect in the production sector. In other words, for every kg of wood less in the domestic per capita consumption almost 0.78 Mt of wood for production, and so, for TRM are required. Further, the dramatic reduction of wood production seen in figure 43-C in the consumption behavior-related scenarios (Refuse, Circularity and Reuse scenarios) is an effect of the deceleration of the construction dynamics boosted by an increase in the demolition rates with no further built environment replacement. Nevertheless, this phenomenon is also perceived in the other scenarios with the exception of the Foreign scenario. Finally, the increase of 140 kg plastic/capita in the domestic market (a 67% increase in comparison to consumption values of 2014) represents an increase of 47% in the production volumes. Wood has the largest impacts in terms of changing per capita consumption, while paper and plastics goods, although still affected have a much lower response to high changes in the consumption values.

### 6.2.3. Domestic consumption

The dramatic changes in the consumption-related scenarios indicate the variability and impact of this variable in the development of the scenario dynamics. The domestic demand is a result from a combination of both the domestic per capita consumption, shown in figure A.3 in Annex A, and the in-use lifetime of products. The domestic per capita consumption is modeled with a linear behavior, as discussed above in section 5.2, with a general growing trend oscillating between a total of 890 kg/cap and 1,100 kg/cap for the three carbon-based materials in 2055.

Because of the shrinking population dynamics, the paper demand volumes illustrated in figure 44-B, showed signs of saturation or decrease in paper goods with the exception of the Refuse scenario. In this scenario a change to an ever increasing domestic demand takes place increasing to 15.3% in 2055 compared to the Baseline scenario. The similar development of the Reuse, Circularity and the Substitution scenarios illustrates the very similar effects that recycling and a potential reduction in paper consumption has. The domestic demand for wood products is quite stable as shown in figure 44-C, as most of the wood-based goods belong to capital goods with very fixed in-use dynamics. However, it experiences the effects of the behavioral patterns in combination with the slow but growing demand. The rapid decrease in the domestic consumption between 2015 and 2030 is the response of the reuse of long-lived products (such as furniture or recovered parts from demolitions). However as the wood purposes shift to energy uses plus the reduction of the construction rate, the behavioral patterns have a lesser impact in lowering the consumption, increasing the final domestic demand. The Substitution scenarios clearly thrives the demand of wood and paper to lower levels compared to the baseline scenario while the plastic demand increased dramatically, as a response to the significant changes of the plastic per capita consumption.

### 6.2.4. Stocks dynamics

The different stock dynamics in figures 45-A to 45-D illustrate the important stock-flow relationships with in the AMS. Three notorious trends were observed. One trend directly bounded to the consumption-related scenarios, a second one which corresponds to the response of the substitution effects and a last one that follows a similar development of the baseline scenario. The Reuse and Circularity scenarios have the largest loss of stocks along the system as these present a reduction in the per capita consumption compared to the Baseline scenario. On the contrary, the Refuse scenario increases stocks due to the increment of the domestic demand.

The short-life of paper stocks are described with decreasing dynamics in figure 45-B. Despite the increment of post-consumer paper wastes in the Refuse scenario, a staggering stock building occurs caused by the increase in the per capita consumption and the relative stable post-consumer waste flow. While paper domestic demand increased to 61 Mt in 2055 (25% more than the Baseline scenario volume), paper waste just had an increment of 2.8 Mt (10.8% more compared to the same scenario). These different rates cause a very quick accumulation of material in the AMS. In this behavior a modeling response to the short in-use lifetime of paper goods and the waste disposal process should be taken into account. The reason relies in the assumption that every single in-use lifetime product has the same discard rates. In others words, in the real world the disposal of paper goods will commonly take place at one time independent of the time of use. The model granularity is not capable of reproducing this effect and therefore a theoretical accumulation of material takes place. Thus, in this scenario the domestic demand is proportionally higher than the expected waste outflows.

Such dramatic differences between the paper stocks are not seen in the wood stocks. Wood products have much longer in-use cycles showing no abrupt changes in stocks, as their dynamic is much slower. No significant increase in wood stocks indicate first a larger use of wood for energy purposes, second more material substitution in wood-related services and third deceleration of the construction rate of dwellings and non-residential buildings. Also three dynamics are seen. In plastics stocks, the increase of per capita consumption has remarkable effects on its stock dynamics. Similar to the production behavior, an increase of one kg plastic/per capita represents a build-up of 0.7 kg in plastic stocks compared to the Baseline scenario. In the Refuse scenario, stocks become larger than the other consumer-related scenarios in 2037, with an increase of 41.4% compared to the Reuse and Circularity scenarios.

### 6.2.5. Post-consumer wastes

The increasing trend of paper wastes shows the clear effect of refuse in short-lived consumer goods. These changes are not so dramatically seen in the other materials groups. In fact, the peak by 2035 of wood post-consumer wastes found in the behavior-related scenarios (Circularity, Refuse and Reuse scenarios) in figure 46-C is caused by reduction of wood stocks. The stocks of in-use products are an indicator of future post-consumer waste flows. Between post-consumer wastes and stock dynamics a 10-year delay for wood products is seen, while for paper and plastics a time between 5 to 7 years is perceived. Specifically, wood stocks peak by 2025, while post-consumer wastes in 2035. Knowing the in-use stock volumes anticipates information timely for a proper waste management.

Further, in plastics the substitution of paper and wood raises the waste volumes speedily and estimate the largest post-consumer waste volumes. Nevertheless, the refuse effects should not be neglected as these also present an increment above the Baseline scenario. The partial substitution of wood and paper goods for plastic products in the Substitution scenarios, increase the plastic post-consumer waste and create an independent dynamic with an increment of almost 90% compared to the baseline scenario as seen in figure 46-D. Thus the increase in per capita consumption of 140 kg/cap shows an almost 1:1 ratio with the waste generation. In other words, 1 kg plastic/per capita increases in similar volume the post-consumer waste volume.

### 6.2.6. Carbon-related emissions

From the evaluated carbon-based materials shown in figure 47 a large variability in the total volumes of carbon emission is observed. Carbon-related emissions within the scenarios range between 81.5 Mt $CO_2$-eq (Circularity scenario) and 114.5 Mt $CO_2$-eq (Substitution scenario). This wide range is caused by the changes in paper and plastic consumer goods affected by behavioral changes. Other scenarios like the Foreign and Substitution plus (+) scenarios described a very similar development compared to the Baseline scenario. In the former, carbon-emissions of exported goods are not accounted as part of the AMS. In the latter, the high recycling rates of plastic limits the energy uses of the post-consumer wastes. In fact, it can be inferred that by increasing in 20% the plastic recycling rates in a Substitution scenario is enough the meet the Baseline scenario carbon emissions volumes. In this scenario the domestic per capita consumption of plastic increments 68%, while paper and wood consumption decreases by 27% and 17%, respectively, compared to the Baseline scenario in 2055. In this same line, it is observed that while the Reuse and Circularity scenarios have the same stock dynamics, the estimated carbon emissions are significantly different, showing the effects of recycling.

Paper-related emissions in figure 47-B experience a reduction until 2025 to begin an increment caused by the changes in consumption patterns and the increment in other services where the paper recyclability is diminished. Further, capital goods show more stable developments along the scenarios, which is seen for example in the wood products in figure 47-C as the carbon emission range is significantly narrower. The behavioral patterns have a smaller impact in such long-lived products from dwellings, non-residential buildings and furniture. Plastic-related carbon emissions shown in figure 47-D do have a larger variability, with a tendency of having growing volumes in the coming years considering the world trend of increasing the use of plastics.

A combination of environmental measures and behavioral patterns proves to be the best alternative to reduce carbon-related emissions for paper and plastic material groups. For the former, the inclusion of an environmental-friendly consumer behavior with an increase in the in-use lifetime of 20% represents a further reduction of 17 Mt $CO_2$-eq (8%) along the simulation. For plastics products the reduction adds 48 Mt $CO_2$-eq (5.4%). On the other hand, the larger volumes experienced in the Circularity scenario compared to the Recycling scenario, in this case 60 Mt $CO_2$-eq along the simulation and a total volume difference of 4%, suggests that the reduction effects come mostly from consumer goods and not capital goods.

In terms of per capita emissions, the change in the consuming patterns (reuse of goods) have a very significant effect in the per capita emissions, reducing on average 200 kg $CO_2$-eq/capita annually compared to the Baseline scenario. On the other side, refuse patterns increases emissions in more or less 100 kg $CO_2$-eq/capita annually. In a very notorious fashion the consequences of recycling are seen between the development of the Reuse and Circularity scenarios, where the latter one cuts more than 110 kg $CO_2$-eq/capita having lower emissions than the Baseline scenario along the whole simulation.

## 6.3. Circularity indicators

With the intention of scrutinizing a deeper perspective of circularity in the material systems, as a measure for a more efficient management of resources and materials, the evaluation of each individual variable is complemented now with a dimensionless normalization of output variables in form of indicators. The goal for achieving a better circularity within the AMS is the reduction of throughput (raw materials, wastes and carbon emissions) or the increment of stock as carbon sinks, in accordance to a SEM perspective. Taking the results of the baseline scenario as standard values, the effects of changes in the scenarios are visualized using a variable-output analysis, where some key relationships are normalized. Four key circularity indicators (or ratios) are defined. These ratios compare the most relevant environmental-oriented variables for understanding the dynamics for circularity in the AMS, namely, SRM, stock dynamics, post-consumer waste and carbon-related emissions. The first indicator describes a secondary- to-domestic raw material ratio (R/D ratio) that evaluates the share of SRM within the domestic resources. The second indicator is a stock-to-emission ratio (S/E ratio) that analyses the stock dynamics in comparison to its associated emissions. The third indicator illustrates a secondary raw material-to-emission ratio (R/E ratio) evaluates the volumes of secondary raw material in comparison to the carbon-related emissions in the same period. The final indicator is the stock-to-waste ratio (S/W ratio) that determines changes in in-use stocks to total post-consumer wastes. All the indicators are estimated within the periodic corresponding values.

Comparing the results to the Baseline scenario gives a perception of the effectiveness and positive impacts. The Baseline scenario is taken as reference since it represents the most possible development of the German carbon-based AMS. The indicators were designed in a way that any result above the Baseline values indicates a better performance in comparison to these scenario, while a result below one (1.0 is the normalized value of the Baseline scenario) indicates a poorer performance of the evaluated ratios. The values for this analysis are taken from the figures 42, 45, 46 and 47 to evaluate the whole material system and each of the material groups. All indicators are estimated using equation (30) comparing each of the variables from the scenarios with the corresponding value of the Baseline scenario. As mentioned above, these figures indicate a normalized dimensionless ratio for the total system and for each material group.

$$\left(\frac{A}{B}\right)_t = \frac{A_{s,t}B_{b,t}}{A_{b,t}B_{s,t}} \; \forall \, s \tag{30}$$

$\textit{with},$

$\left(\frac{A}{B}\right)_t$ = *Circularity indicator*

$A_{s,t}$ = *Value of variable A in alternative scenario s at period t*

$B_{b,t}$ = *Value of variable B in Baseline scenario at period t*

$A_{b,t}$ = *Value of variable A in Baseline scenario at period t*

$B_{s,t}$ = *Value of variable B in alternative scenario s at period t*

$s$ = *Alternative scenario*

### 6.3.1. The R/D indicator

The R/D indicator is the first dimensionless normalized indicator to measure the degree of circularity in the AMS. It establishes a relationship between the SRM used volumes coming from domestic post-consumer wastes to total domestic raw material requirements. This latter variable excludes imported raw materials. Figures 49-A to 49-D illustrate the secondary raw

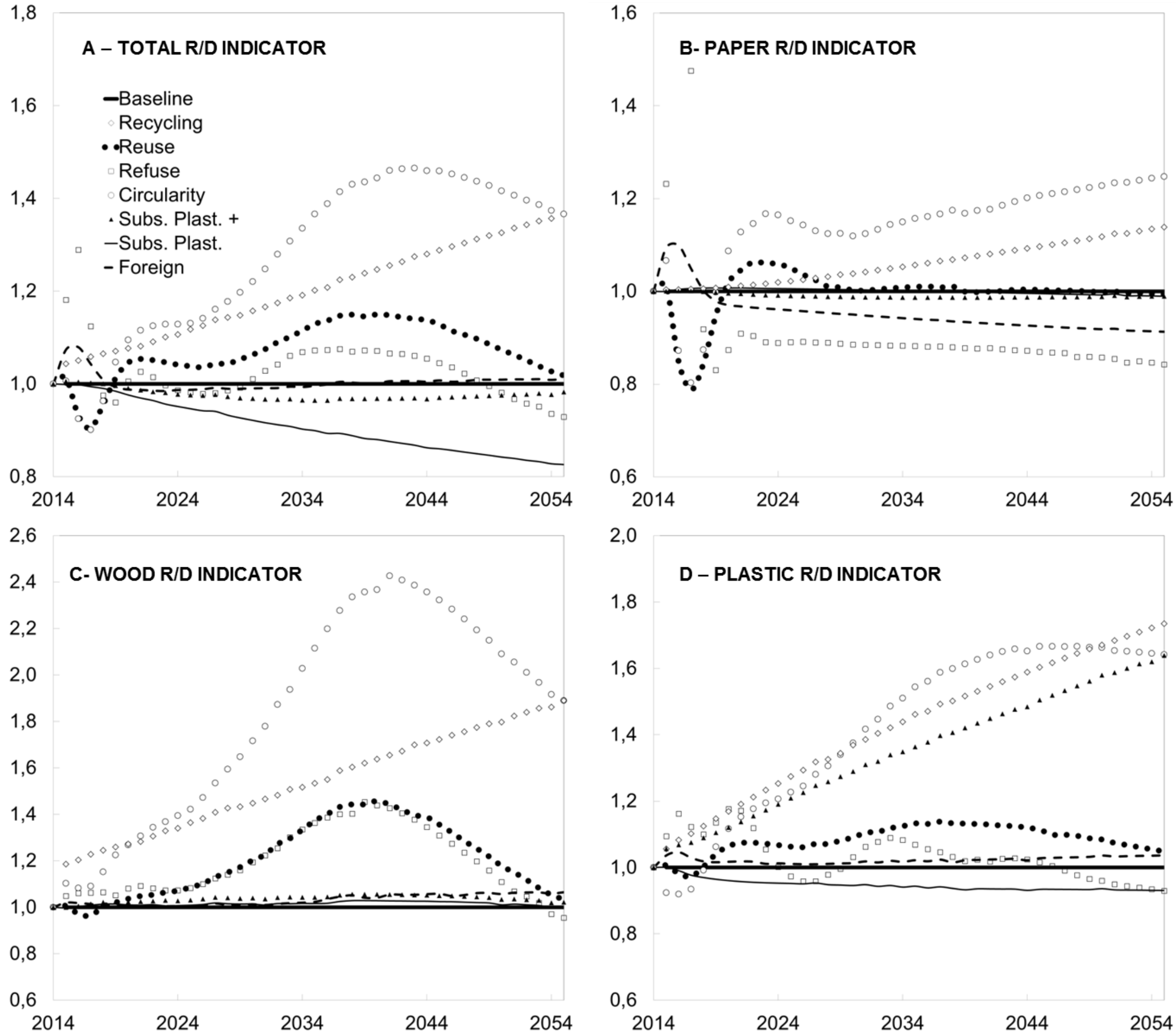


Figure 49: R/D (secondary-to-total domestic raw materials) indicator dynamics between 2015 and 2055

material-to-total domestic raw material ratio (or R/D indicator) for the total carbon-based system and for each of the evaluated carbon-based materials. The domestic raw materials volumes and not the total raw materials volume are evaluated to evaluate the impact of the different scenarios within the economy-wide AMS. It also contributes to describe the challenges faced with domestic resource availability. The quantitative ratio between these two raw material sources is shown in figure A.4 in Annex A.

In figure 49-A, the total R/D indicator for the behavior-related scenarios (Reuse, Refuse and Circularity scenarios) and the Recycling scenario show positive improvement compared to the Baseline scenario. The Refuse scenario presents the lowest changes with even negative results after 2050, while the Circularity scenario staggers rapidly and peaks with a value of nearly 1.5 by 2040, to finally meet with the Recycling scenario values by 2055. The latter scenario describes a permanent growth of the R/D indicator. The Substitution scenarios do not show any significant improvement indicating larger consumption volumes of plastics and further utilization of post-consumer waste for energy purposes. Further, figure 49-B shows relative stable dynamics suggesting saturation in the R/D indicator. A noticeable improvement in both Circularity and Recycling scenarios indicate that almost all the domestic raw materials come from recovered paper, with potentials to create a surplus, mostly targeted for exports. On the contrary, the Refuse scenario presents the lowest R/D indicator value showing the impact of higher demand of raw materials caused by the increase of domestic per capita consumption.

The R/D indicator for wood products in figure 49-C shows for the Circularity, Reuse and Refuse scenarios a different dynamic compared to the paper R/D indicator. The rapid increase and subsequent reduction in the R/D indicator after 2040 is a response first to changes in the consumption patterns reducing the domestic raw materials share for materials purposes and second the effects of decreasing stocks dynamics by the changes mostly in infrastructure and buildings construction rates. Besides the behavior-related scenarios, in figure 49-D the Substitution plus (+) scenario also present positive results. This scenario shows similar behavior to the Recycling scenario. The constant growth in the Substitution plus (+) scenario is also given by the staggering plastic per capita consumption in combination with the high waste recovery rates. This indicates that if the current trend of recycling is incremented and one-third of the plastics are recycled for material uses, it is possible to achieve equivalent R/D indicator values when the domestic per capita consumption of plastics increases.

### 6.3.2. The R/E indicator

The secondary raw material-to-emission ratio (R/E indicator) evaluates the required SRM in comparison to the carbon-related emissions in the same period. Recycling is a main component of the development of circularity in material systems. Thus, SRM contrary to PRM are a better indicator for resource demands within the evaluated AMS considering possible behavioral consumption patterns, as well as, overuse and subsequent depletion of resources. A high value of this indicator highlights larger volumes of available SRM in combination with lower carbon emissions.

In figure 50-A the R/E indicator presents slow dynamics or a decrease caused mainly by the stagnation of SRM and because of a slight reduction in the consumption of PRM, excepting the Recycling and Circularity scenarios. Both SRM and PRM are very sensitive variables environmentally speaking, as the latter is directly linked to the demand of new natural resources. The effects of recycling (expressed as an increase in the SRM) are very clearly seen in both Substitution scenarios, where the R/E indicator the Substitution decreases reaching 0.86 by 2055, while the Substitution plus (+) rises to 1.1 in the same year. The positive response it is even more notorious in figure 50-D. In the Foreign scenario the indicator also presents a positive balance. However, it is associated with the reduction of carbon-emissions caused by the increase in the foreign per capita consumption that displaces (and reduces) a volume of post-consumer waste outside the AMS.

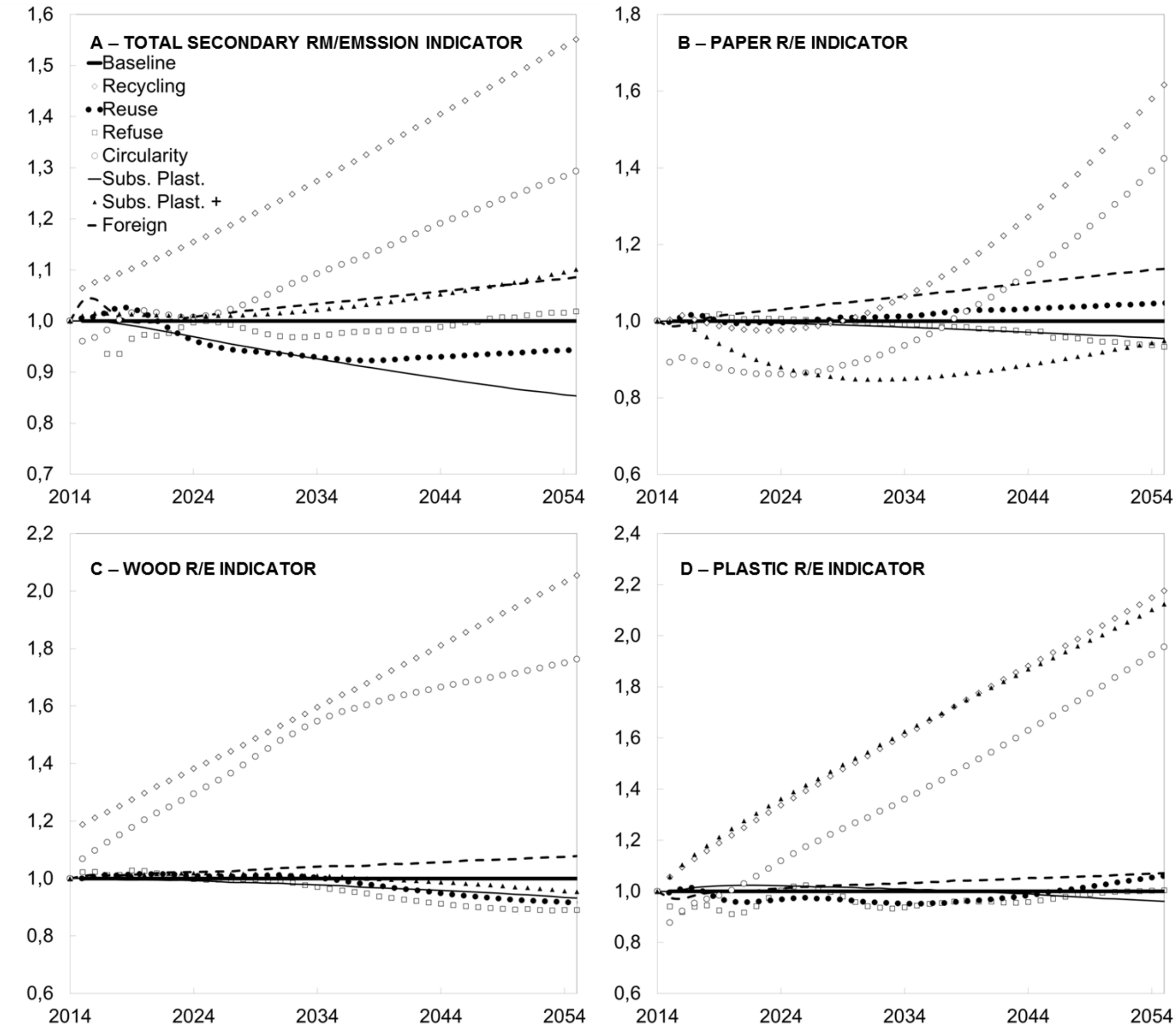


Figure 50: R/E (SRM-to-carbon-related emissions) indicator dynamics between 2015 and 2055

Figures 50-C and 50-D show the positive effects in the Recycling and Circularity scenarios. Without doubt, the Recycling and Circularity scenarios show the best performance in the R/E indicator in all three carbon-based materials, improving between 1.6 to 2.1-fold the ratio compared to the Baseline scenario, while the resting scenarios do not show significant differences.

### 6.3.3. The S/E indicator

In figure 51-A the carbon in-use stock-to-emissions ratio (S/E indicator) of the complete AMS is illustrated. Keeping in mind that, carbon stocks are seen as carbon sinks, a high S/E indicator value describes a system where an increase of stocks is happening or a cutback in its emissions. A low S/E value shows systems with a high potential of carbon emissions. The Recycling scenario shows a better performance with a reduction in the carbon-related emissions. Further, the Reuse scenarios begins with a positive development, but very swiftly a drastic reduction in the stocks takes place with a small change in the carbon emissions. Therefore, it presents a negative development compared to the Baseline scenario. In the last years of the simulation, an improvement in the S/E indicator is seen as the carbon-related emissions begin to sink. The Reuse scenario has the worst performance, while the Substitution scenarios have an increase in the carbon emissions, caused by the very low

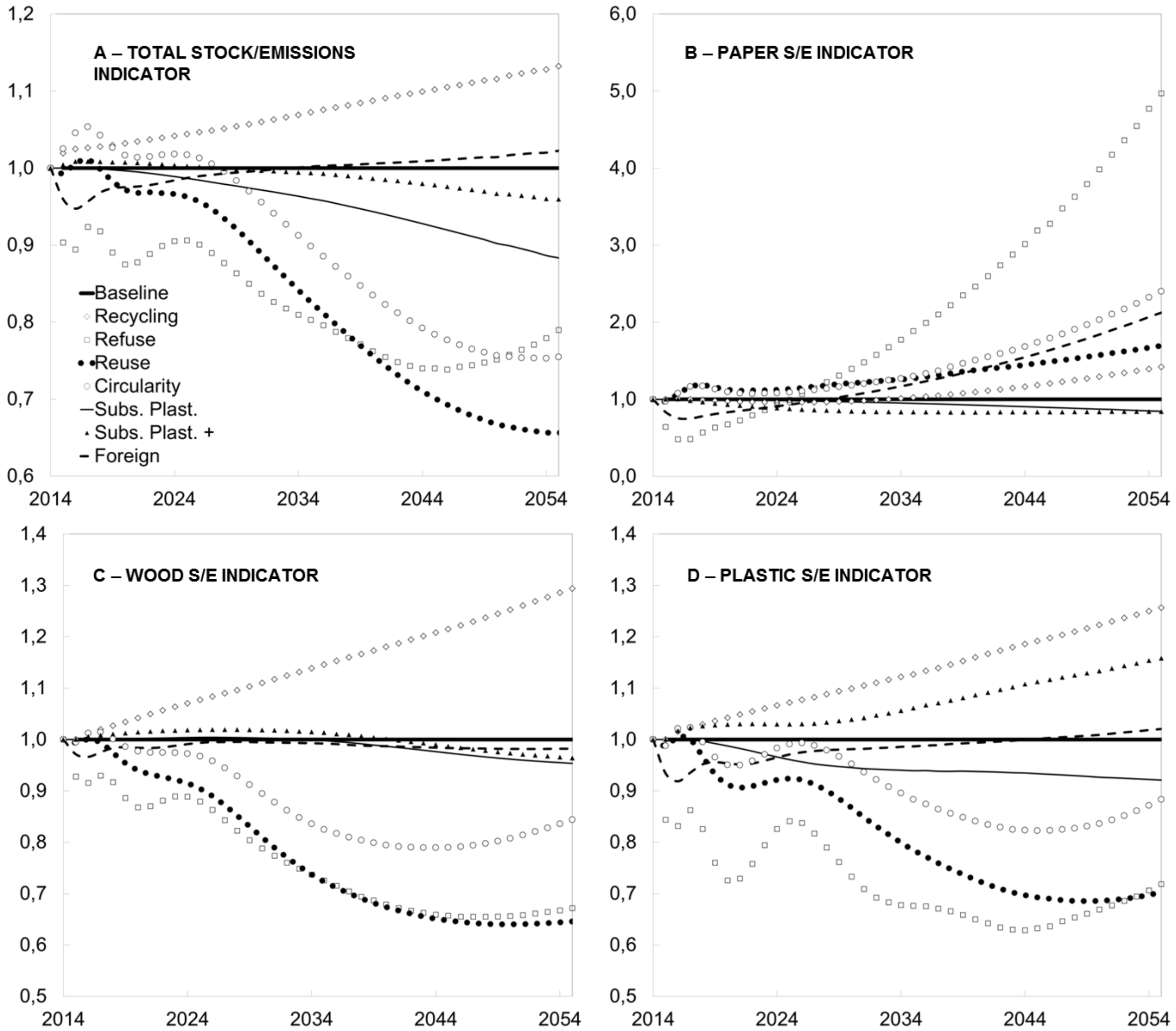


Figure 51: S/E (In-use carbon stock-to-carbon-related emissions) indicator dynamics between 2015 and 2055

recycling rate of plastic post-consumer wastes. It is shown however, that recycling and changes in consumption patterns (refuse of goods) have a positive effect in the S/E indicator, despite the reduction in the carbon stocks and in carbon-related emissions as illustrated in figures 45 and 47. A mere change in behavior or consumption patterns, favors the S/E indicator, but in the long term, as the stocks begin to reduce the indicator can decrease below one meaning a transition of in-use stocks into carbon in the atmosphere. This means a transition of in-use stocks into carbon emissions. For long-lived capital goods in wood and plastic a negative effect with a reduction in the S/E indicator is also observed in figures 51-C and 51-D, as lower volumes of in-use stocks are further incorporated. This illustrates the potential impact of carbon stocks as future carbon sources.

Figures 51-B describes the paper S/E indicator. A notorious improvement is seen in the Refuse scenario and not so dramatic in the Recycling scenario. In the other scenarios a small dynamic is perceived. For paper consumer goods in figure 51-B, a change of behavior (reuse of goods) is not favorable to reduce carbon emissions, and should be complemented with improvements in the recycling rates. This is seen with the Circularity scenario where although also facing a similar consumption pattern it rapidly increases its value to improve the indicator by 2036. In figure 51-C only a higher recycling shows an improvement compared to the rest of the scenarios. The effect of recycling is not only seen in the Circularity scenario, but in the Substitution scenarios. A substitution of paper and wood products for plastic products is expected. This has a negative effect in the emissions, as shown in figure 51-D, where the dynamics with the Substitution scenario are below one. Nevertheless, increasing the recycling rate from 11% to 31% (which is a very optimistic value for recycling of plastics), changes dramatically the S/E indicator above one; for instance, reducing the carbon emission by 9.1Mt $CO_2$-eq in 2055.

### 6.3.4. The S/W indicator

The stock-to-waste ratio (S/W indicator) seeks to identify the potential for increasing in-use stocks parallel to a reduction in the post-consumer waste. The low values in the S/W indicator for most of the scenarios suggest a proportional linear relationship between both variables. It is observed a faster reduction in in-use stocks as in post-consumer waste volumes, with the exception of short-lived consumer paper goods as observed in figures 52-B. In the behavior-related scenarios the S/W indicator has a cutback until around 2040 when a slight deceleration in the dynamic and the value levels-off or even shows signs of recovery shown figures 52-A, 52-C and 52-D.

The change in the dynamic obeys the time-delay response between both variables. This relationship is illustrated in figure 52-B by the very rapid increase in the indicator, where the effects in stocks, because of the short in-use lifetime has a significant effect. This indicator is mostly driven by the per capita consumption as only the scenarios were this variable changes describe a more dynamic development. Recycling processes on the contrary, show a minor effect. A configuration to increase carbon stocks and reduce simultaneously post-consumer wastes has a small opportunity for improvement within a time lapse of 40 years for capital goods.

The circularity indicators comprehend a systematic assessment of the most relevant variables in the carbon-based AMS, with the aim of comparing the results of the alternative scenarios with the baseline scenario development under a dimensionless normalization of the evaluated variables. This dynamics indicate the influence in the changes of modeling variables and their effects in the relevant outputs for achieving a better circularity of the AMS. The analysis was performed in a quantitative way, as a guide for highlighting potential and efficient values in setting targets for recycling rates, in-use lifetime of goods or domestic per capita consumption of carbon-based materials.

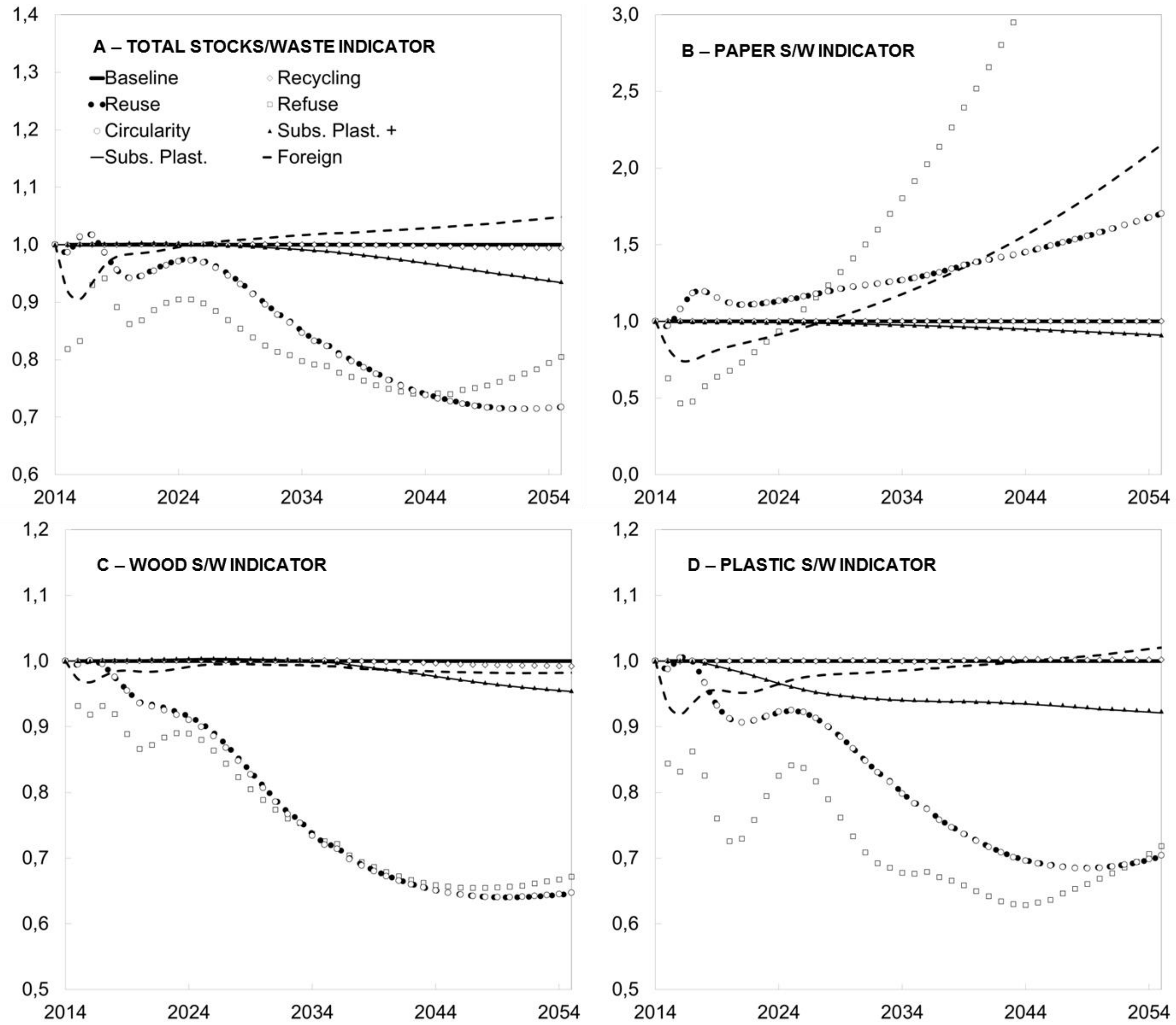


Figure 52: S/W (In-use carbon stocks-to-post-consumer wastes) indicator dynamics between 2015 and 2055

## 7. Moving towards material circularity in the anthroposphere

Anthropogenic environments have become a fundamental object of study and analysis for understanding the behavior, development and state of current societies. Since the introduction of the socioeconomic metabolism (SEM) paradigm in the late 1990s (Fischer-Kowalski and Hüttler, 1998) and further development and application (Brunner and Rechberger, 2004; Baccini and Brunner, 2012; Pauliuk and Hertwich, 2015; Schandl et al., 2015), it has become a response to the growing environmental and technical challenges in the anthroposphere and in anthropogenic material systems (AMS). SEM has given context and significance to the role and impact of human needs and activities (economic, social, biological, cultural, among others) within the systemic balance between the biogenic and anthropogenic systems. The dynamic balance of deliberately induced material and energy throughputs is achieved with the description, characterization and quantification of flows and stocks, including feedback loops. Flows and stocks are part of the basic structure and pattern of reality and it describes the utmost relationships, development and functioning of many current anthropogenic and natural systems. Even more, the study of anthropogenic flows and stocks has gained awareness, as the scarcity of natural resources is increasingly notorious.

In addition, carbon has become one of the main societal drivers. The versatility for material and energy purposes are fundamental for the reaching a state of development and welfare. The main carbon-based materials in the anthroposphere are paper, wood, plastics and rubber and are relevant materials with high carbon content. Paper and wood final goods have nearly 43% C w/w, while plastics and rubber products contain around 50 to 60% C w/w (Young, 2010). Furthermore, carbon has gained a negative reputation as one of the largest contributors of the human-induced climate change. Around 80% of the carbon emissions are coming from energy activities (Wilke, 2013). However, the potential emissions from non-energy use, that is, material use from carbon stocks, should not be underestimated (Kohlmaier et al., 2007; Rüter, 2008; Köhl et al., 2009; OECD, 2010a). Carbon creates carbon sinks with a large potential capacity of carbon emissions to the atmosphere (Gielen, 1997). Understanding the dynamics of carbon flows and stocks within the AMS is an essential step for the development of a sustainable carbon management under the SEM perspective and the transition to low-carbon circular economies (CE).

Nowadays, the CE concept has reached political spheres and has become an important step in the decoupling of resources, pollution and social welfare (EC, 2015a; Schandl et al., 2015; BMUB, 2015). Nevertheless, it should go beyond the economic level to be able to describe thoroughly the dynamic balance and systemic behavior of an AMS. In a broader sense, the term circularity has been adopted as a generalization of the CE concept, for efficient use of resources and sound management of recycled post-consumer wastes in order to reduce the burden of anthropogenic activities in the ecosystems. The concept of circularity should be universally applicable. Since AMS are open systems with constant input and output requirements to maintain functionality, it is not a goal to achieve a closed system. Notwithstanding, sociotechnical and environmental improvements in the system should be elucidated with the goal of achieving a better material circularity in the anthroposphere. The study and analysis of carbon-based AMS can play a fundamental role in the pressure alleviation of new resources knowing the amounts and composition of carbon-based materials, its consumption, stocks and post-consumer wastes dynamics, and carbon-related emissions.

For a comprehension of these dynamics, an economy-wide stock-flow model was developed, to study and analyze carbon-based materials from a service-oriented approach using Germany as case study. As one of the most developed export-oriented and vibrant economies worldwide, this country becomes an excellent case-study to examine and study the carbon-based AMS dynamics. Taking the model structure of a previous IO-based static carbon flow model – CarboMoG (Uihlein, 2007), in combination with the Material Flow Analysis (MFA) methodology, the evaluation of a carbon-based AMS was possible. The model, first, evaluated from a descriptive point of view (modeling with statistical-based time-series) the dynamics of the carbon-based German material system from 1929 to 2014, and, second, from a prospective approach (scenario analysis), the possible developments of the AMS through 2055. Based on current trends and plausible changes, seven alternative scenarios were evaluated under different social, technical and environmental contexts. The model provided a thorough insight of the relationships between carbon resources, stock dynamics, post-consumer waste generation and carbon emissions.

The expected development and dynamic of an economy-wide carbon-based material system between 1929 and 2014 under a SEM perspective in Germany was thoroughly described and analyzed from a systemic approach. In addition, and based on a solid description of past periods, the following forty years (2015-2055) of a carbon-based AMS have also been thoroughly evaluated.

Nowadays, 70.5 Mt of carbon-based raw materials are required for the satisfaction of needs in the German anthroposphere. It is expected to increase to 96.3 Mt by 2055. From these volumes nearly three-quarters come from primary sources and one-quarter from secondary sources. Despite the shrinking population dynamics an increase in the consumption of goods from the current 65.3 Mt of final goods to 70.9 Mt in 2055 is observed. Currently, from this total 31.7% correspond to paper goods, 57.7% to wood products and 16.6% to plastic goods. The demand of paper might suffer a slight stagnation. However, the paper industry is keen to develop new applications maintaining a constant domestic demand (Dispan, 2013b). The wood industry will maintain a slow but growing dynamic in the domestic demand, driven mostly by the increase of wood for energy purposes. In this sense, the wood use is being shift to energy uses reaching 56% of the total domestic demand. The plastic industry has a strong potential to grow, especially with the increasing demands of foreign markets and the versatility of its polymer matrices in new applications. Services like packaging and communication from plastic products, present rapid growth dynamics in domestic demand. The rapid dynamic of plastics consumption and its even wider use in consumer and capital goods, shows a permanent increase of plastics stocks for the coming 40 years.

From a total of 413.1 Mt of carbon-based material in-use stocks are in Germany, 32.6 Mt are paper goods (7.9%), 304.6 Mt wood products (73.7%) and 75.9 Mt plastic products (18.4%). This indicates a current stock per capita of 398 kg of paper, 3.8 tons of wood and 951 kg of plastics, respectively. Paper stocks will suffer a reverse in the coming decades, while wood stocks will continue to growth at least for 30 more years. In fact, wood is the largest carbon-based material used in the German anthroposphere with a large utilization in built environments. Nevertheless, because of the shrinking population, it is expected a reduction by 13%. This cutback also affects other wood industries like the furniture and panel industry, as this are closely related with the construction sector. Paper goods will face a change in services, as the communication service loses almost 50% of its market share. This represents a decrease in the in-use stock and subsequently reduction in the post-consumer wastes.

A total of 42.1 Mt of post-consumer waste are currently generated and will increase to around 51.5 Mt in 2055. The largest share comes from the paper products with 20.3 Mt (48.2%), followed by the wood products (excluding final goods for energy purposes) with 13.3 Mt (31.6%) and closing with a volume of plastics waste of 8.4 Mt (19.9%). Post-consumer waste flows of wood and plastic will continue to increase reaching levels of 17.5 and 14.2 Mt, respectively in 2055. This means an increase of 22% for wood and 39% of plastics compared to 2014. For paper products, a volume around 20.8 Mt is expected in the coming years and a slight decrease after 2030 is seen to reach 19.7 Mt in 2055. Recovered paper has reached almost a saturation point with no large further increases. Despite the drastic reduction of paper waste for communication services, the volumes of paper post-consumer waste will remain constant. Further, an increase in the post-consumer waste outflows volumes, especially in plastic products is plausible, caused mainly by the growing applications of plastics in consumer and capital goods, and the substitution of wood for some products. Wood waste outflows have by far the largest carbon-based material waste distribution, but will face a slight stagnation in the last decade (2040-2050) as the effects of the deceleration of new built environments is taken place.

Plastics post-consumer wastes are currently used for energy purposes and should focus in increasing the recycled share to reduce carbon-emissions and raw material requirements. The better use of plastics in the anthroposphere is also perceived and it proves a challenge to cope with carbon emissions from non-renewable sources. The current trend of replacing plastics as an alternative fuel should be re-evaluated and improve the use of plastics in material purposes as a measure to create carbon sinks for longer periods of time. An even larger share of final wood use for energy purposes is expected. The first reason is the changes in the market shares as wood for new built environments are less demanded. This creates a secondary effect with a reduction in the furniture industry. Thus, the material use of wood will suffer a decrease, added to the continuous development of plastic-based materials that replace wood-based final foods.

Recycling of paper has reached a mature stage, leading to stagnation in the volumes of secondary raw materials in addition to the reduction of paper waste outflows. Therefore, it is important to initiate effective recycling strategies for wood and plastics which still have low rates. Increases in the recycling rate of these two latter carbon-based materials show significant improvement in the circularity indicators and a reduction in the TRM.

Carbon-related emission will continue to increase, with the exception of the emission from landfills. A total volume of 92.1 Mt $CO_2$-eq of carbon material-related emissions are released nowadays to the atmosphere and these will continue to rise crossing the 100 Mt $CO_2$-eq level around 2031. Carbon emissions will continue to grow, with a rising share from non-renewable sources. In part because plastics have a very high energy content at a low cost and are very attractive as secondary fuel or alternative fuel resource. Positive effects of incineration of post-consumer plastics on climate change are minor. Thus, the increase of use plastic recyclates for material purposes guarantees the capture of carbon in the material, and should be considered as a serious mechanism for the use of these types of wastes, as shown in the scenario analysis. In terms of per capita emissions, no reduction is observed except when reuse consumer behavior is adopted and recycling rates are improved. The combination of both leads to a significant reduction of carbon-related emissions.

Using a scenario approach, complex relationships between the different technological, social and environmental aspects of the material system were investigated. Within the dynamics of AMS, several opportunities are foreseeable in the coming decades for efficient management of carbon-related resources, post-consumer wastes and related emissions. With the study of seven alternative scenarios (namely, Refuse, Reuse, Circularity, Recycling, Substitution, Substitution+ and Foreign) focused on specific changes in the AMS, a significant understanding about the dynamics and behavior of the complete carbon-based material system was achieved. Information about the raw material requirements, post-consumer waste volumes and composition, as well as carbon-related emissions have been in detailed evaluated.

Although recycling proved to be a very efficient measure for decreasing the pressures in PRM, the role of the consumers showed a dramatic impact in the whole dynamic balance of the system. Recycling is a very effective way for the reduction of carbon material-related emissions. Even more, the impact of in-use lifetime of goods, not only influences stocks dynamics but has also significant impacts in carbon-related emissions and SRM availability. For instance, changes of 20% in the in-use lifetime of consumer goods increased the per capita consumption between 6% and 19%. For capital goods (built environments and infrastructure) the variation of the in-use lifetime relies more at a policy level as consumer do not have the capacity of significantly affect the use of non-residential buildings or infrastructure. It was observed, that increasing the recycling rates in paper bring little benefit for the domestic material system, as the total domestic raw materials are almost covered by secondary sources. A large potential for increasing the material use of domestic post-consumer waste is seen for plastics and wood.

Short in-use lifetime goods and stocks are very sensitive to changes in consumption demands. This can be caused by changes in consumption patterns or by social factor as population changes. In the case of Germany, population is playing a determinant role, not only on short and middle in-use lifetime products, but also in the long and very-long in-use lifetime goods. The shrinking dynamic of the German population estimates a reduction from circa 82 million in 2014 to nearly 68 to 70 million in 2055. This is a major concern for the whole German government, as it implicates unknown and counteracting effects on the economy and the manufacturing sector. In this sense, the Foreign scenario showed that an export-oriented policy is one way to cope with this phenomenon as production maintains above baseline scenario levels. Also, an improvement of both manufacturing and recycling efficiencies under an environmental perspective are a measure for optimization of natural resources use, recovery of post-consumer wastes for secondary raw materials and a mechanism for coping with undesirable emissions to the biosphere. Finally, carbon emissions depend on one hand, to long-term carbon stock building coming, for example, from built environments (mostly wood products), and on the other hand, to the substitution potential of fossil-fuels in energy processes.

Starting with the concept of circular economy, the term circularity was introduced with the interest of generalizing a larger scope of the AMS, which included not only economic aspects, but also technical, social, political and environmental. Using own-developed circularity indicators, the extent that circularity of a carbon-based AMS can be achieved to create carbon sinks and tackle current environmental burdens was explored. With the design of four circularity indicators, the scenario results are compiled in the most relevant information to understand the dynamics of the AMS. These were focused on resource demands, stocks dynamics, post-consumer waste and carbon emissions.

The defined indicators were (1) secondary raw material-to-total domestic raw material ratio or 2/D indicator, (2) carbon in-use stock-to-emissions ratio or S/E indicator, (3) secondary raw material-to-emission ratio or R/E indicator, and (4) carbon in-use stock-to-waste ratio or S/W indicator. It was observed with the circularity indicators that not only recycling plays a fundamental role as source of SRM, also consumption behavior influence positive and negative the dynamics of the AMS. For instance, an increment of 6% in the paper recycling fraction will signify an increase of 20% in the secondary-to-domestic raw material requirements. In plastics an optimistic change of 11% to 31% in the recycling rate reduces carbon emissions by 9.1 Mt $CO_2$-eq by 2055. Reuse consumption patterns reduces carbon stocks and at the same time cutbacks carbon emissions.

Because of its flexibility and the principles of mass balance embedded in the model, it can be applied at several system boundary levels, say from a household, to industries, regions, countries, or even the whole world. Thus, it is a reliable and practical tool to provide an initial overview of a system. The level of granularity in some aspects of this model can be, however, improved. The developed model proved to be an adequate tool for the evaluation in the development and dynamics of economy-wide anthropogenic material systems. A thorough description of carbon-based materials in the German anthroposphere was performed showing the dynamics and transformation of the system under stock-flow relationships. Carbon is a very significant element which requires important attention and understanding of its dynamics within AMS, with the aim of providing knowledge about coping with carbon emissions, reducing pressure for raw materials and moving towards sustainable low-carbon societies.

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## Annex A: Complementary model information and results

In this annex, complementary information used for the modeling of the anthropogenic material system is presented. Also, further results which were not included in the main body are shown here.

### A.1. Mathematical mass balance formulation for system sectors

Equation (A.1) describes the whole anthropogenic material system boundary (see figure 3) under an economy-wide perspective, containing flows of raw materials, exports, imports, wastes, emissions and stocks change. Exports and imports include final goods and secondary raw materials.

$$\boldsymbol{R_t^{dom} + R_t^{imp} + X_t^{imp} + W_t^{imp} - W_t^{ldf} - X_t^{exp} - R'^{exp}_t - C_t - \Delta S_t = 0} \tag{A.1}$$

$\boldsymbol{with,}$
$\boldsymbol{R_t^{dom}}$ = $\boldsymbol{Domestic\ processed\ primary\ raw\ materials\ (kt/a)}$
$\boldsymbol{R_t^{imp}}$ = $\boldsymbol{Imported\ processed\ primary\ raw\ materials\ (kt/a)}$
$\boldsymbol{X_t^{imp}}$ = $\boldsymbol{Imported\ goods\ (kt/a)}$
$\boldsymbol{W_t^{imp}}$ = $\boldsymbol{Imported\ post - consumer\ waste\ for\ waste\ treatment\ processes\ (kt/a)}$
$\boldsymbol{W_t^{ldf}}$ = $\boldsymbol{Post - consumer\ waste\ for\ lanfills\ (kt/a)}$
$\boldsymbol{X_t^{exp}}$ = $\boldsymbol{Exported\ goods\ (kt/a)}$
$\boldsymbol{R'^{exp}_t}$ = $\boldsymbol{Exported\ secondary\ raw\ materials\ (kt/a)}$
$\boldsymbol{C_t}$ = $\boldsymbol{Total\ carbon\ content\ in\ materials\ for\ combustion\ processes\ (kt\ C/a)}$
$\boldsymbol{\Delta S_t}$ = $\boldsymbol{Stock\ change\ in\ the\ anthroposphere\ (kt/a)}$

Figures 6 (production sector), 7 (market sector), 8 (consumption sector), 10 (waste management sector) and 11 (combustion sector) illustrate the flows and stocks for each sector used for the mass balance calculation. The equations below describe these sectors mathematically. Equation (A.2) describes the product manufacturing sector.

$$\boldsymbol{R_t^{dom} + R_t^{imp} + R'^{re}_t + X_t^{ru} - X_t^{dom} - W_t^{man} = 0} \tag{A.2}$$

$\boldsymbol{with,}$
$\boldsymbol{R_t^{dom}}$ = $\boldsymbol{Domestic\ processed\ primary\ raw\ materials\ (kt/a)}$
$\boldsymbol{R_t^{imp}}$ = $\boldsymbol{Imported\ processed\ primary\ raw\ materials\ (kt/a)}$
$\boldsymbol{R'^{re}_t}$ = $\boldsymbol{Recycled\ raw\ materials\ (kt/a)}$
$\boldsymbol{X_t^{ru}}$ = $\boldsymbol{Reused\ or\ refused\ goods\ (kt/a)}$
$\boldsymbol{X_t^{dom}}$ = $\boldsymbol{Domestic\ manufactured\ goods\ (kt/a)}$
$\boldsymbol{W_t^{man}}$ = $\boldsymbol{Waste\ from\ manufacturing\ processes\ (kt/a)}$

Equation (A.3) describes the market sector.

$$X_t^{dom} + X_t^{imp} - X_t^{exp} - D_t = 0 \tag{A.3}$$

$$
\begin{aligned}
&\textbf{with},\\
&X_t^{dom} &&= \textit{Domestic manufactured goods } (kt/a)\\
&X_t^{imp} &&= \textit{Imported goods } (kt/a)\\
&X_t^{exp} &&= \textit{Exported goods } (kt/a)\\
&D_t &&= \textit{Domestic demand } (kt/a)
\end{aligned}
$$

Equation (A.4) describes the consumption sector.

$$D_t - W_t - X_t^{ru} - F_t - \Delta S_t = 0 \tag{A.4}$$

$$
\begin{aligned}
&\textbf{with},\\
&D_t &&= \textit{Domestic demand } (kt/a)\\
&W_t &&= \textit{Post} - \textit{consumer waste from consumption } (kt/a)\\
&X_t^{ru} &&= \textit{Reused or refused goods } (kt/a)\\
&F_t &&= \textit{Domestic energy goods } (kt/a)\\
&\Delta S_t &&= \textit{Stock change in the anthroposphere } (kt/a)
\end{aligned}
$$

Equation (A.5) describes the solid waste management sector.

$$W_t + W_t^{man} + W_t^{imp} - W_t^{ldf} - W_t^{inc} - R'^{exp}_t - R'^{re}_t = 0 \tag{A.5}$$

$$
\begin{aligned}
&\textbf{with},\\
&W_t &&= \textit{Post} - \textit{consumer waste } (kt/a)\\
&W_t^{man} &&= \textit{Post} - \textit{industrial waste } (kt/a)\\
&W_t^{imp} &&= \textit{Imported post} - \textit{consumer waste for waste treatment processes } (kt/a)\\
&W_t^{ldf} &&= \textit{Post} - \textit{consumer waste for landfills } (kt/a)\\
&W_t^{inc} &&= \textit{Post} - \textit{consumer waste for incineration and energy purposes } (kt/a)\\
&R'^{exp}_t &&= \textit{Exported secondary raw materials } (kt/a)\\
&R'^{re}_t &&= \textit{Recycled raw materials } (kt/a)
\end{aligned}
$$

## A.2. Domestic and foreign consumption

Figure A.1 illustrate the estimated per capita consumption of paper, wood and plastic for Germany and worldwide, based on historic data (Consultic, 2007; Consultic, 2009; Consultic, 2011; Consultic, 2013; Weimar, 2013; Mantau et al., 2012a; Bilitewski, 2005; FAO, 2009). The dotted curved describe historic and statistical time-series from the literature. The continuous curve corresponds to the logistic regression for the period 1929-2055. Because of the limited information, some of the initial values were assumed, like the 1929-value for world per capita consumption of wood and plastic. Final values (year 2055) are estimated based on expected production growths (VCI and Prognos AG, 2013; FÖP and Ökopol, 2013; Mantau et al., 2010a).

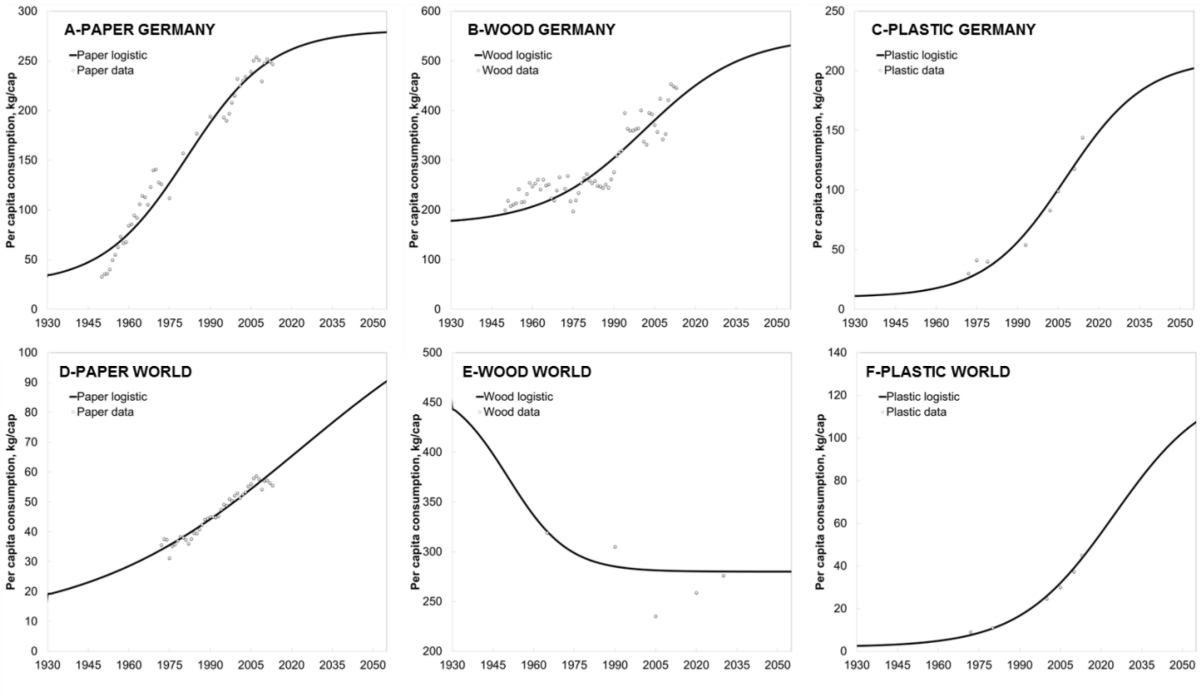


Figure 53: Estimated per capita consumption of paper, wood and plastic for Germany and the world between 1930 and 2055

Based on these results linear regressions are made for the prospective modeling, in order to avoid “multiple” pasts obtained from the logistic regression. Table A.1 provides the linearized initial and final values with its corresponding growth for the baseline scenario.

Table 10: Estimated linear annual growth rates and per capita consumption of paper, wood and plastic in 2055 for baseline scenario, kg/cap

| | 2014 | 2055 | Growth, yr |
|---|---|---|---|
| Germany | | | |
| Paper goods, kg/cap | 254.8 | 279.1 | 0.3% |
| Wood goods, kg/cap | 429.2 | 532.9 | 0.5% |
| Plastic goods, kg/cap | 133.9 | 203.1 | 0.9% |
| World | | | |
| Paper goods, kg/cap | 61.6 | 91.7 | 1.3% |
| Wood goods, kg/cap | 280.6 | 280.1 | 0.0% |
| Plastic goods, kg/cap | 46.9 | 109.2 | 2.1% |

*Sources:* VCI and Prognos AG, 2013; FÖP and Ökopol, 2013; FAOSTAT 2013; Consultic, 2013; FAO 2009; Mantau, Wagner and Baumann, 2005

Figure A.2 illustrates the consumption values of the service infrastructure for the baseline scenario, which are discussed in section 5.3.3.

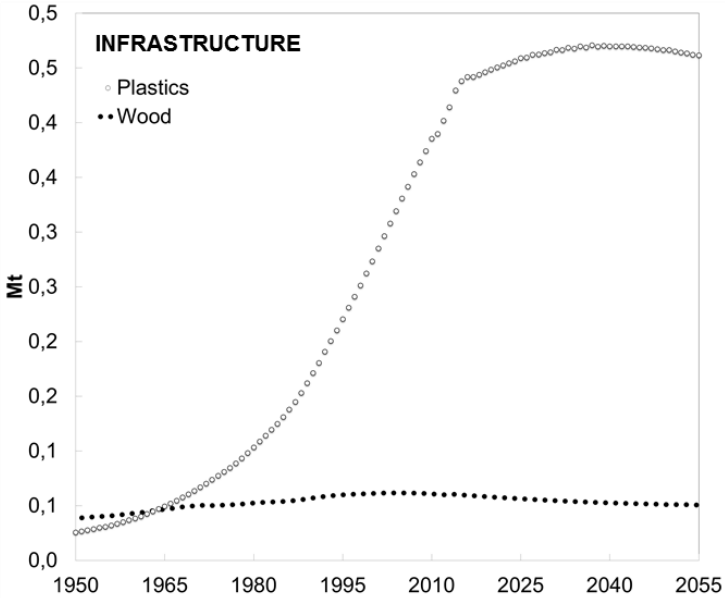


Figure 54: Domestic demand of infrastructure service, Mt

## A.3. In-use lifetime

The in-use lifetime categorization of products is shown in table 6. Each product group has an estimated minimum, maximum and expected in-use lifetime. Values were taken from the literature (Aktas, 2011; EcoFys, 2011; Schiller et al., 2015; Höglmeier et al., 2013; Murakami et al., 2010) or in some cases assumed. In some cases the in-use lifetimes were deduced from renovation rates, such as in dwellings and offices, as well as its components like doors,

Table 11: Change in the in-use lifetime of consumer and capital goods for the Reuse scenario

| Service - Material | ST | MD | LG | VL |
|---|---|---|---|---|
| Packaging - Paper | 1.20 | – | – | – |
| Packaging - Wood | 1.20 | – | – | – |
| Packaging - Plastic | 1.20 | – | – | – |
| Well-being - Paper | 1.10 | – | – | – |
| Well-being - Plastic | 1.20 | 1.20 | – | – |
| Well-being - Wood (Including Energy) | 1.00 | 1.20 | – | – |
| Communication - Paper | 1.20 | – | – | – |
| Communication - Plastic | – | 1.20 | – | – |
| Transportation - Plastic | – | 1.20 | – | – |
| Well-being - Commodities non-res. - Wood | – | – | 0.8 | – |
| Well-being - Commodities non-res. - Plastic | – | – | 1.10 | – |
| Well-being - Commodities res. - Wood | – | – | 0.8 | – |
| Well-being - Commodities res. - Plastic | – | – | 1.10 | – |
| NRB + Infrastructure -Wood | – | 0.80 | 0.80 | 0.80 |
| NRB + Infrastructure -Plastic | – | 0.80 | 0.80 | – |
| Residential buildings - Wood | – | – | 0.80 | 0.80 |
| Residential buildings - Plastic | – | – | 0.80 | – |

*Comments:* ST: Short in-use lifetime; MD: Middle; LG: Long; VL: Very long; NRB: Non-residential buildings flooring, windows, and so on (EcoFys, 2011; Aktas, 2011). In general, in-use lifetimes remain invariable during the scenario analysis. However, consumer behavior is described by the change of the expected and maximum in-use lifetime for each product group. A value of 1.0 is given to the standard in-use lifetime values in the baseline scenario. Values larger than 1.0 indicate a reuse consumption pattern (longer in-use lifetime), and values smaller than 1.0 indicate a refuse consumption pattern (shorter in-use lifetimes). Table A.2 exemplifies the assumed consumption patterns for each of the services and materials for the Reuse scenario, where a longer in-use lifetime for consumer goods is assumed. In the refuse case, values are set to 0.8.

## A.4. Industry information

### A.4.1. Manufacturing losses within the industries

The manufacturing efficiency estimates the material loss per unit of mass used for the production of final goods. The calculated values for the manufacturing efficiencies are between 0.80-0.95 for paper products (Hashimoto et al., 2004; COST, 2010); around 0.93 for wood products (Nebel et al., 2006; Mantau et al., 2010b); and 0.92 for plastics (Consultic, 2013). For energy use of wood no manufacturing efficiencies are taken into account. Within the manufacturing process of final goods and at recovery states of post-consumer and post-industrial wastes material losses occur. A quantification of material losses, on one side measures the process efficiencies and degree of usefulness of recovered materials. Based on statistical information overall manufacturing efficiencies and recycling depollution factors are estimated for each material group as shown in table A.3.

Table 12: Manufacturing efficiency and recycling depollution factor (source: own calculations)

| Material | Manufacturing | Recycling |
|---|---:|---:|
| Paper | 0.82 | 0.95 |
| Wood | 0.93 | 0.80 |
| Plastic | 0.92 | 0.90 |

Not all the waste is capable of being recycled, caused by content of inappropriate substances or materials, or low qualitative characteristics. Thus in real terms, the recycling process has losses depending on paper and board grade. According to COST (2013), the material losses for packaging grades are between 8% and 12%, for publication papers between 15% and 20% and for hygiene papers between 35% and 40%. The recycling depollution factor allocates the amounts of post-consumer and post-industrial waste with potential for recycling from the non-recyclable traces. At the recycling process post-consumer and post-industrial wastes are converted into secondary raw materials. The recycling depollution factor integrates qualitative and technical recovery aspects.

According to Mantau et al. (2010), processing of woody raw materials have material losses between 0.7% and 1.6% for coniferous and non-coniferous timber respectively. Further material losses occur during the manufacturing of semi-finished products like particle board (3.94%), MDF (9.61%) or veneer and plywood (45.0%), among others. These loses are assumed to stay outside the anthropogenic boundary. However, material loses in industrial branches are taken into consideration. The estimated material losses for the construction sector is 10.3%, for the furniture industry (18.4%), packaging industry (9.7%) and other industries (13.0%) values are also given (Mantau et al., 2010a). Further, manufacturing residues and sawdust are further used for the production of pellets. For plastics, the manufacturing efficiencies are around 7.3% (Consultic, 2013), and in recycling processes it is assumed to be around 10%.

### A.4.2. Shares of manufactured goods

Industrial information is used as guidance for some model inputs. For example, table A.4 presents the approximate shares of manufactured goods per services for plastic goods (Consultic, 2013). These values are used to validate the results obtained after the modeling process.

Table 13: Plastic applications in terms of services in 2013

| Packaging | | Construction | | Transport | | Electronic | |
|---|---|---|---|---|---|---|---|
| Films | 38.0% | Profiles | 33.0% | Interiors | 53.0% | Cables | 34.0% |
| Carrying bags | 11.5% | Pipes | 14.3% | Exteriors | 19.5% | White goods | 22.5% |
| Containers <5L | 15.5% | Insulation | 6.6% | UtH | 15.0% | IT | 11.5% |
| Containers >5L | 4.5% | Other | 2.5% | Electric/Light | 12.5% | Brown goods | 6.5% |
| Bowls/Cans | 14.0% | – | – | – | – | Other | 25.5% |
| Seals | 9.0% | – | – | – | – | – | – |
| Other | 7.5% | – | – | – | – | – | – |

Comments: White goods: refrigerator, stoves, washing machines, and so on; Brown goods are typically household electrical entertainment appliances; UtH “Under the hood” refers to plastic parts in the engine area.

### A.4.3. Incineration data of post-consumer wastes

Table A.5 presents incineration data for the estimation of carbon emissions in terms of $CO_2$-eq. At the combustion process the liberation of carbon in terms of carbon dioxide and other combustion gases occur. Because of the material mixture of carbon-based materials, values of elementary analysis should be used to estimate concentrations of carbon, nitrogen, oxygen and additional elements that compose these materials. Carbon-based materials have medium to high content of carbon, ranging between 43% (dry wood) to 65% (plastics) C w/w, and content of nitrogen less than 0.5% N w/w (Lemann, 2008; Young, 2010). Concentrations of hydrogen (H), oxygen (O) and sulphur (S) are in this case not relevant. Table A.6 gives the elementary average composition of the material groups.

Table 14: Incineration data for the estimation of carbon-related emissions

| Combustion gas | GC | GWP | ξ |
|---|---|---|---|
| Carbon dioxide ($CO_2$) | 0.992 | 1 | 3.67 |
| Carbon monoxide (CO) | 0.006 | n.a. | 2.33 |
| Methane ($CH_4$) | 0 | 25 | n.a. |
| Nitrous oxide ($N_2O$) | 0.0008 | 320 | 3.14 |
| Other gases | 0.0072 | n.a. | n.a. |

Sources: Mendes, Aramaki and Hanaki, 2004; Klein and Kubisa, 1994. *Comments:* GC = kg gas / Σ kg gas; GWP = Global warming potential; ξ = Stoichiometric combustion ratio

Table 15: Elementary average composition of product and raw material groups

| Material group | C | H | O | N | S | W | A |
|---|---|---|---|---|---|---|---|
| Paper - final goods | 0.43 | 0.06 | 0.44 | 0.01 | 0.01 | 0.05 | 0.05 |
| Wood - final goods | 0.43 | 0.06 | 0.44 | 0.01 | 0.01 | 0.05 | 0.05 |
| Plastic - final goods | 0.60 | 0.07 | 0.23 | 0.00 | 0.00 | 0.00 | 0.10 |
| Paper - raw materials | 0.49 | 0.06 | 0.44 | 0.02 | 0.02 | 0.05 | 0.05 |
| Wood - raw materials | 0.49 | 0.08 | 0.33 | 0.50 | 0.10 | 0.05 | 0.05 |
| Plastic - raw materials | 0.83 | 0.13 | 0.04 | 0.01 | 0.00 | 0.05 | 0.10 |

*Sources:* Lemann, 2008; Young, 2010; Mendes, Aramaki and Hanaki, 2004; C:Carbon, H:Hydrogen, O:Oxygen, N:Nitrogen, S:Sulfur, W:Water, A:Ash content (w/w)

## A.5. Scenario analysis

Complementary information for the scenario analysis is given as follows. Figures A.3 illustrates the changes in the domestic per capita consumption for each scenario.

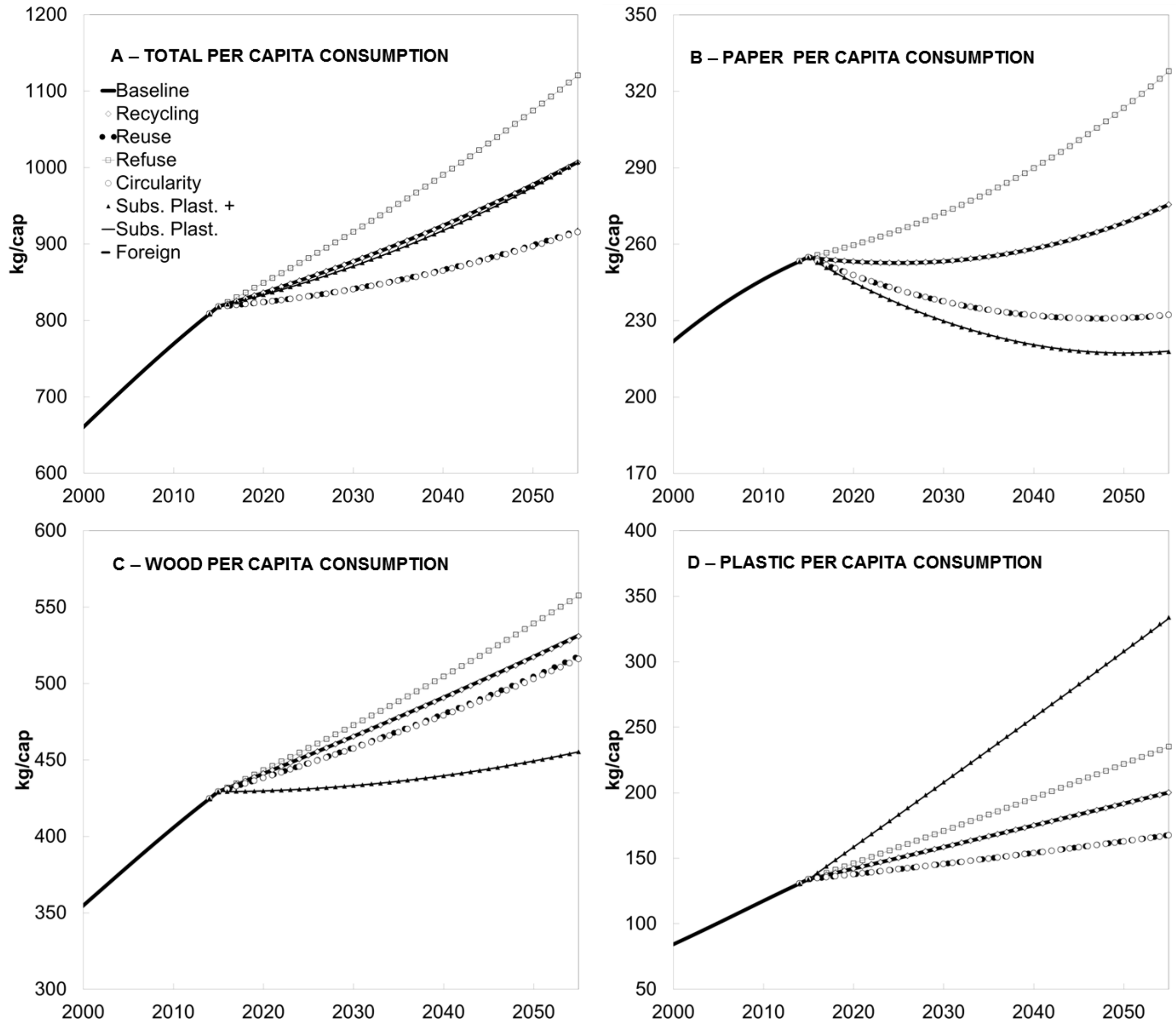


Figure 55: Scenario results of domestic per capita consumption from carbon-based materials, kg/cap

Table A.7 summarizes the changes in the market shares caused by the different scenarios. This illustrates the effects of consumer choice or changes in the dynamics of services.

Table 16: Market share service dynamics for scenario modeling in 2055

| Service | 2014 | Baseline | Recycling | Reuse | Refuse | Circular | Substi. | Substi.+ | Foreign |
|---|---|---|---|---|---|---|---|---|---|
| Paper products | | | | | | | | | |
| Packaging | 36.0% | 39.6% | 39.6% | 39.6% | 39.6% | 39.6% | 25.2% | 25.2% | 39.6% |
| Well-being | 48.10% | 24.1% | 24.1% | 24.1% | 24.1% | 24.1% | 28.9% | 28.9% | 24.1% |
| Communication | 15.8% | 36.3% | 36.3% | 36.3% | 36.3% | 36.3% | 45.9% | 45.9% | 36.3% |
| Wood products | | | | | | | | | |
| Packaging | 8.60% | 8.60% | 8.60% | 9.46% | 9.46% | 9.46% | 6.02% | 6.02% | 8.60% |
| Heating | 44.50% | 53.88% | 53.88% | 57.71% | 58.20% | 58.20% | 61.7% | 61.7% | 53.88% |
| Well-being | 16.79% | 13.44% | 13.44% | 11.76% | 14.28% | 14.28% | 12.6% | 12.6% | 13.44% |
| Residential | 13.96% | 11.17% | 11.17% | 9.77% | 8.38% | 8.38% | 9.07% | 9.07% | 11.17% |
| Non-residential | 15.82% | 12.66% | 12.66% | 11.08% | 9.49% | 9.49% | 10.28% | 10.28% | 12.66% |
| Infrastructure | 0.32% | 0.26% | 0.26% | 0.19% | 0.23% | 0.19% | 0.26% | 0.26% | 0.26% |
| Plastic products | | | | | | | | | |
| Packaging | 33.34% | 33.34% | 33.34% | 36.68% | 36.68% | 36.68% | 41.68% | 41.68% | 33.34% |
| Well-being | 26.90% | 29.59% | 29.59% | 30.94% | 30.94% | 30.94% | 22.87% | 22.87% | 29.59% |
| Communication | 7.92% | 9.51% | 8.71% | 9.51% | 9.51% | 9.51% | 7.13% | 7.13% | 9.51% |
| Residential | 6.47% | 5.17% | 5.17% | 3.88% | 3.88% | 3.88% | 6.47% | 6.47% | 5.17% |
| Non-residential | 12.01% | 9.61% | 9.61% | 7.20% | 7.20% | 7.20% | 11.41% | 11.41% | 9.61% |
| Transport | 9.28% | 9.51% | 10.31% | 9.35% | 9.35% | 9.35% | 6.78% | 6.78% | 9.51% |
| Infrastructure | 4.08% | 3.27% | 3.27% | 2.45% | 2.45% | 2.45% | 3.67% | 3.67% | 3.27% |

Further, the information used in figure 30 about the changes in the waste management processes in Germany is given the table A.8. The reduction of landfilled post-consumer wastes is regulated since 2005.

Table 17: Estimated post-consumer waste treatment distributions in Germany

| Process - Material | 1930 | 1970 | 2010 | 2050 |
|---|---|---|---|---|
| Recycling[a] | | | | |
| Paper | 15.0% | 23.0% | 66.0% | 75.0% |
| Wood | 25.0% | 25.0% | 23.0% | 23.0% |
| Plastic | 20.0% | 20.0% | 14.0% | 11.0% |
| Combustion[b] | | | | |
| Paper | 43.0% | 34.0% | 16.0% | 11.0% |
| Wood | 40.0% | 40.0% | 71.0% | 77.0% |
| Plastic | 15.0% | 15.0% | 75.0% | 86.0% |
| Exported waste | | | | |
| Paper | 2.0% | 4.0% | 12.0% | 14.0% |
| Wood | 15.0% | 15.0% | 3.0% | 1.0% |
| Plastic | 5.0% | 5.0% | 4.0% | 3.0% |
| Landfilling | | | | |
| Paper | 40.0% | 40.0% | 5.0% | 0.0% |
| Wood | 20.0% | 20.0% | 3.0% | 0.0% |
| Plastic | 60.0% | 60.0% | 8.0% | 0.0% |

*Comments:* a) Recycling of materials for domestic use; b) includes energy and non-energy uses of waste

## A.6. Production function coefficients

The production function coefficients indicate the average raw material requirements for the manufacturing of a product group unit. These coefficients were estimated from (Hischier, 2007; Consultic, 2013; Deilmann et al., 2014; Kozlowski, 2006; Tillmann, 2000; Blechschmidt et al., 2000) or in some cases assumed and summarized in table A.9.

## A.7. Circularity indicators

In figure A.4 the comparison for between the secondary raw materials and the total domestic raw materials (excluding the imported raw materials) describe the quantitative volumes coming from secondary sources. As seen in figure A.4-A, the paper ratio is saturated (nearly 100%) indicating that the raw material volumes used in the paper production come from secondary and domestic sources. An increase of 6% in the paper recycling rate will signify a increase of 20% in the secondary-to-domestic raw material requirements. The increases to 119.5% and 130% in the Recycling and Circularity scenarios suggest that higher recovery rates will mostly bring significant benefit for exporting purposes of SRM. The Refuse and Foreign scenarios suffer a decrease of 14% and 5%, respectively. The R/D indicator for wood products in figure A.4-B displays a lower Baseline scenario value around 24%. The Circularity and Recycling scenarios show a different dynamic compared to the paper indicator. The former scenario starts with a value of 24% in 2014, increments to reach a peak of 67% in 2044 and a subsequent decrease to 54% by 2055.

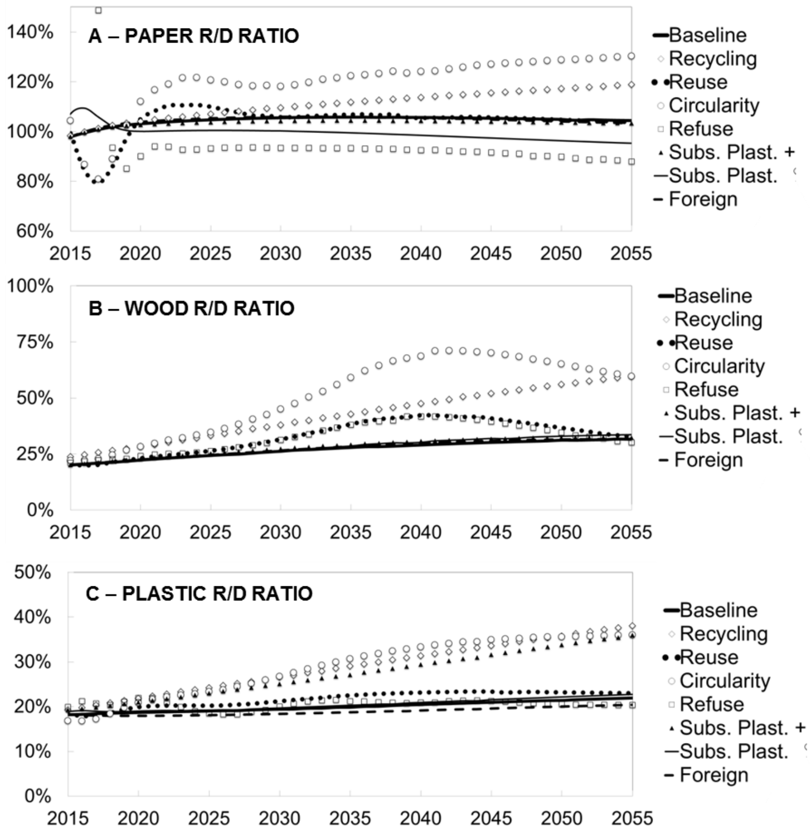


Figure 56: Secondary-to-total domestic raw materials ratio per material group

In figure A.4-C, besides the Circularity and Recycling scenarios, the Substitution scenarios also present positive results. The Substitution plastic plus (+) scenario shows similar behavior to the Recycling scenario reaching a ratio of 36% in 2055. This states clearly the positive effects of this waste management process. The total increase of 18% in 2055 could be correlated with the assumed improvement in the recycling ratio of 20%, as the two variables of this indicator are very closely related to this change.

Table 18: Production function coefficients for processed raw materials for manufacturing of goods (own calculations)

| Product group | CP | MP | SW | PW | M/HDF | CPB | OSB | VN | OW | ADW |
|---|---|---|---|---|---|---|---|---|---|---|
| Short in-use lifetime (ST) | | | | | | | | | | |
| Paper - Bags/Boxes | 0.67 | 0.10 | – | – | – | – | – | – | | 0.23 |
| Wood - Pallets/Boxes/Drums | – | – | 0.51 | 0.34 | – | 0.14 | – | – | – | – |
| Plastic - Containers/Bottles | – | – | – | – | – | – | – | – | – | – |
| Plastic - Bags | – | – | – | – | – | – | – | – | – | – |
| Plastic - Films | – | – | – | – | – | – | – | – | – | – |
| Paper - Hygiene | 0.90 | – | – | – | – | – | – | – | – | 0.10 |
| Paper - Other paper uses | 0.80 | 0.10 | – | – | – | – | – | – | – | 0.10 |
| Plastic - Household appliances[a] | – | – | – | – | – | – | – | – | – | – |
| Wood - Energy-/ Fuelwood | – | – | 1.00 | – | – | – | – | – | – | – |
| Paper - Printed material | 0.63 | 0.13 | – | – | – | – | – | – | – | 0.24 |
| Middle in-use lifetime (MD) | | | | | | | | | – | |
| Wood - Flooring | – | – | 0.04 | 0.02 | 0.84 | – | – | – | | – |
| Plastic - Flooring/Rugs | – | – | – | – | – | – | – | – | 0.10 | – |
| Wood - Boards/Planks[b] | – | – | 0.10 | 0.30 | – | 0.30 | 0.30 | – | – | – |
| Wood - Plates/Panels | – | – | – | 0.30 | – | 0.30 | 0.40 | – | – | – |
| Plastic - Personal vehicles[c] | – | – | – | – | – | – | – | – | – | – |
| Plastic - Public vehicles[d] | – | – | – | – | – | – | – | – | – | – |
| Plastic - Load vehicles[e] | – | – | – | – | – | – | – | – | – | – |
| Plastic - Electric applicances[f] | – | – | – | – | – | – | – | – | – | – |
| Wood - Other products[g] | – | – | 0.50 | – | 0.10 | – | – | 0.10 | – | – |
| Plastic - Medical applications | – | – | – | – | – | – | – | – | 0.30 | – |
| Plastic - Other products[h] | – | – | – | – | – | – | – | – | – | – |
| Long in-use lifetime (LG) | | | | | | | | | – | |
| Wood - Doors/Windows | 0.41 | – | 0.35 | 0.13 | 0.02 | 0.02 | – | – | | 0.02 |
| Plastic - Doors/Windows | – | – | – | – | – | – | – | – | 0.05 | – |
| Plastic - Ducts/Cables/Insulation | – | – | – | – | – | – | – | – | – | – |
| Wood - Furniture (residential) | – | – | 0.30 | 0.13 | 0.10 | 0.20 | 0.15 | 0.15 | – | 0.02 |
| Plastic - Furniture (residential) | – | – | – | – | – | – | – | – | – | – |
| Wood - Furniture (non-residential) | 0.20 | – | – | 0.20 | 0.14 | 0.31 | 0.10 | 0.05 | – | – |
| Plastic - Furniture (non-residential) | – | – | – | – | – | – | – | – | – | – |
| Plastic - Canalization/sewage | – | – | – | – | – | – | – | – | – | – |
| Wood - Transport sector | – | – | 0.90 | – | – | – | – | – | – | 0.10 |
| Plastic - Electricity sector | – | – | – | – | – | – | – | – | – | – |
| Very long in-use lifetime (VL) | | | | | | | | | – | |
| Wood - Staircases | – | – | 1.0 | – | – | – | – | – | | – |
| Wood - Load-bearing structures | – | – | 0.82 | 0.17 | – | – | – | – | – | 0.01 |
| Wood - Frames[i] | – | – | 0.46 | 0.33 | – | 0.01 | 0.20 | – | – | – |

Note: CP = Chemical pulp; MP = Mechanical pulp; SW = Sawnwood; PW = Plywood; M/HDF = Middle and High density Fiberboard; CPB = Chip particle board; OSB = Oriented strand board; VN = Veneer; OW = Other Woods; ADW = Glues, paints, protection layers; a) Kitchen/Bathroom/Non-electric devices; b)Rooms/Kitchen; c)Cars/SUV/Motorbikes; d)Buses/Trains; e)Trucks; f)PCs/TVs/Telephones; g)Toys/Instruments/etc.; h)Textiles/Toys/Instruments/etc.; i)Walls/Roofs

Table A.9 (continuation): Production function coefficients for processed raw materials for manufacturing of goods (own calculations)

| Product group | LDPE | HPDE | PP | PS | PVC | PET | PUR | OT | ADP |
|---|---|---|---|---|---|---|---|---|---|
| Short in-use lifetime (ST) | | | | | | | | | |
| Paper - Bags/Boxes | – | – | – | – | – | – | – | – | – |
| Wood - Pallets/Boxes/Drums | – | – | – | – | – | – | – | – | – |
| Plastic - Containers/Bottles | 0.16 | 0.19 | 0.14 | 0.08 | 0.10 | 0.29 | – | 0.04 | – |
| Plastic - Bags | 0.47 | 0.29 | 0.21 | – | – | – | – | 0.03 | – |
| Plastic - Films | 0.43 | 0.12 | 0.40 | – | – | – | – | 0.05 | – |
| Paper - Hygiene | – | – | – | – | – | – | – | – | – |
| Paper - Other paper uses | – | – | – | – | – | – | – | – | – |
| Plastic - Household appliances[a] | 0.40 | 0.05 | 0.11 | 0.09 | – | 0.01 | – | 0.31 | 0.03 |
| Wood - Energy-/ Fuelwood | – | – | – | – | – | – | – | – | – |
| Paper - Printed material | – | – | – | – | – | – | – | – | – |
| Middle in-use lifetime (MD) | | | | | | | | | |
| Wood - Flooring | – | – | – | – | – | – | – | – | – |
| Plastic - Flooring/Rugs | – | – | 0.06 | 0.28 | 0.37 | – | 0.09 | 0.14 | 0.06 |
| Wood - Boards/Planks[b] | – | – | – | – | – | – | – | – | – |
| Wood - Plates/Panels | – | – | – | – | – | – | – | – | – |
| Plastic - Personal vehicles[c] | – | 0.04 | 0.25 | – | 0.01 | – | 0.10 | 0.57 | 0.03 |
| Plastic - Public vehicles[d] | 0.08 | 0.15 | – | 0.04 | – | 0.17 | 0.51 | 0.05 | |
| Plastic - Load vehicles[e] | – | 0.10 | 0.17 | – | 0.05 | – | 0.05 | 0.60 | 0.03 |
| Plastic - Electric applicances[f] | 0.10 | 0.02 | 0.17 | 0.07 | 0.03 | 0.01 | 0.05 | 0.48 | 0.07 |
| Wood - Other products[g] | – | – | – | – | – | – | – | – | – |
| Plastic - Medical applications | 0.12 | 0.13 | – | 0.16 | – | 0.01 | – | 0.54 | 0.04 |
| Plastic - Other products[h] | 0.10 | 0.04 | 0.16 | 0.02 | 0.03 | – | – | 0.62 | 0.03 |
| Long in-use lifetime (LG) | | | | | | | | | |
| Wood - Doors/Windows | – | – | – | – | – | – | – | – | – |
| Plastic - Doors/Windows | 0.04 | 0.08 | 0.11 | – | 0.52 | – | 0.13 | 0.08 | 0.04 |
| Plastic - Ducts/Cables/Insulation | 0.01 | 0.22 | 0.05 | 0.19 | 0.27 | – | 0.06 | 0.18 | 0.01 |
| Wood - Furniture (residential) | – | – | – | – | – | – | – | – | – |
| Plastic - Furniture (residential) | – | 0.02 | 0.21 | – | 0.09 | – | 0.23 | 0.42 | 0.04 |
| Wood - Furniture (non-residential) | – | – | – | – | – | – | – | – | – |
| Plastic - Furniture (non-residential) | – | 0.02 | 0.21 | – | 0.09 | – | 0.23 | 0.42 | 0.04 |
| Plastic - Canalization/sewage | 0.02 | 0.15 | – | 0.07 | 0.50 | – | – | 0.24 | 0.02 |
| Wood - Transport sector | – | – | – | – | – | – | – | – | – |
| Plastic - Electricity sector | 0.03 | 0.24 | 0.11 | – | 0.39 | – | 0.11 | 0.08 | 0.04 |
| Very long in-use lifetime (VL) | | | | | | | | | |
| Wood - Staircases | – | – | – | – | – | – | – | – | – |
| Wood - Load-bearing structures | – | – | – | – | – | – | – | – | – |
| Wood - Frames[i] | – | – | – | – | – | – | – | – | – |

Note: LDPE = Low-density polyethylene; HPDE = High-density polyethylene; PP = Polypropylene; PS = Polystyrene; PVC = Polyvinyl-chloride; PET = Polyethylene-terephthalate; PUR = Polyurethane; OT = Other Thermoplastics; ADP = Glues, paints; a) Kitchen/Bathroom/Non-electric devices; b)Rooms/Kitchen; c)Cars/SUV/Motorbikes; d)Buses/Trains; e)Trucks; f)PCs/TVs/Telephones; g)Toys/Instruments/etc.; h)Textiles/Toys/Instruments/etc.; i)Walls/Roofs

## Annex B: Uncertainty and sensitivity analysis

The procedure and some results of the uncertainty and sensitivity analysis were presented and discussed in section 3.4. Complementary results are presented as follows.

### B.1. Uncertainty analysis

The MCS were performed on a 10-year modeling period as the effects over the evaluated variables could be seen within this range. Because of time constraints, each simulation lasted nearly 15 min, a total of 1094 simulations were performed. This fairly good number of results provided the behavior of uncertainty in selected input variables. The MCS is performed with the Oracle Excel-based application “Crystal Ball” used for predictive modeling, forecasting, and simulation, among others. Output results are then analyzed to evaluate the sensitivity of the model corresponding to the input data, as discussed below. As mentioned in section 3.4, some of the input data uncertainty was determined from different sources: statistical data, expert based approximations with or without probabilistic distributions, and assumptions. Table B.1 summarizes the used ranges for each variable in the Montecarlo Simulation (MCS) and table B.2 the main results. All values follow a PERT distribution. The PERT distribution is an alternative to a triangle distribution, with considerably higher sensitivity to the most likely value than to the maximum and minimum value, reducing the potential systematic bias problem of the triangle distribution. This advantage also reflects lower values in standard deviations. Also, the shape of the PERT distribution is highly flexible as shown in figure 13. A main drawback of the PERT distribution lies in the skewness of its shape that can reduce the density in extreme values, making sometimes the maximum and minimum values meaningless. For the uncertainty analysis the PERT distributions will be used for the input data in all cases.

### B.2. Monte Carlo Simulation

The additional histograms from the wood and plastic material groups are shown in figures B.1 and B.2. Normal distributed trends are seen in all cases, with an exception in the waste outflow of wood (W-5 in figure B.1). This output factor has a very positive skew and no normal distribution. This latter variable is an outlier, caused by the short modeling time. The MCS also shows that in most cases results lay within the first two quartiles.

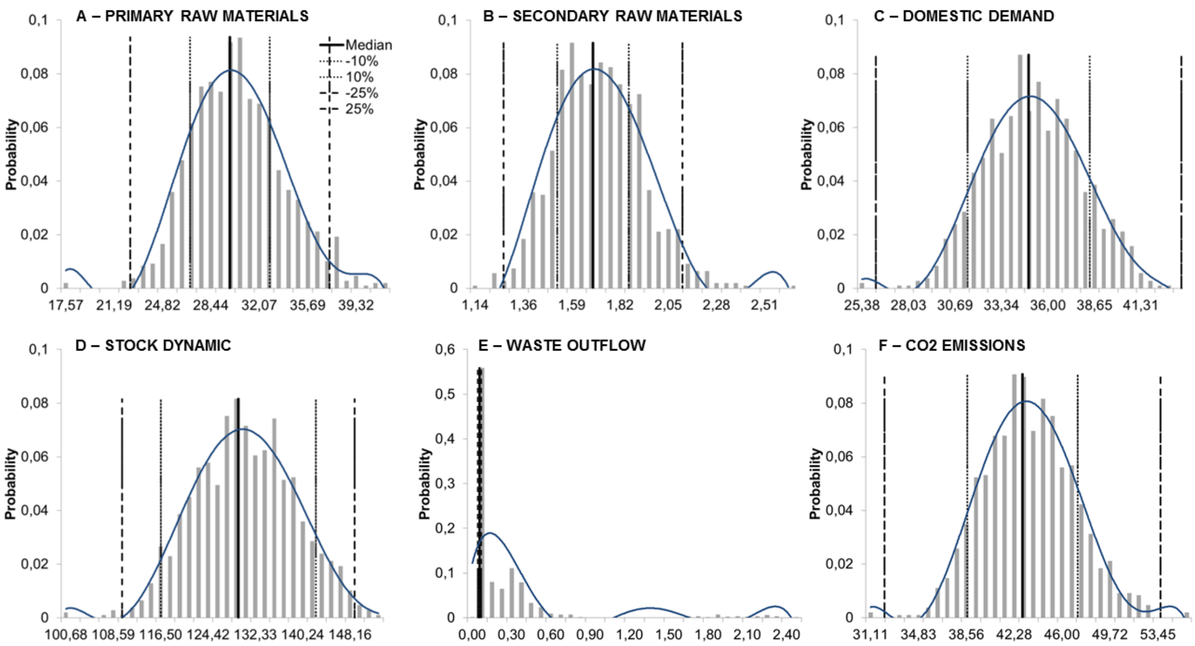


Figure 57: Results for output factor from a Monte Carlo simulation for wood products

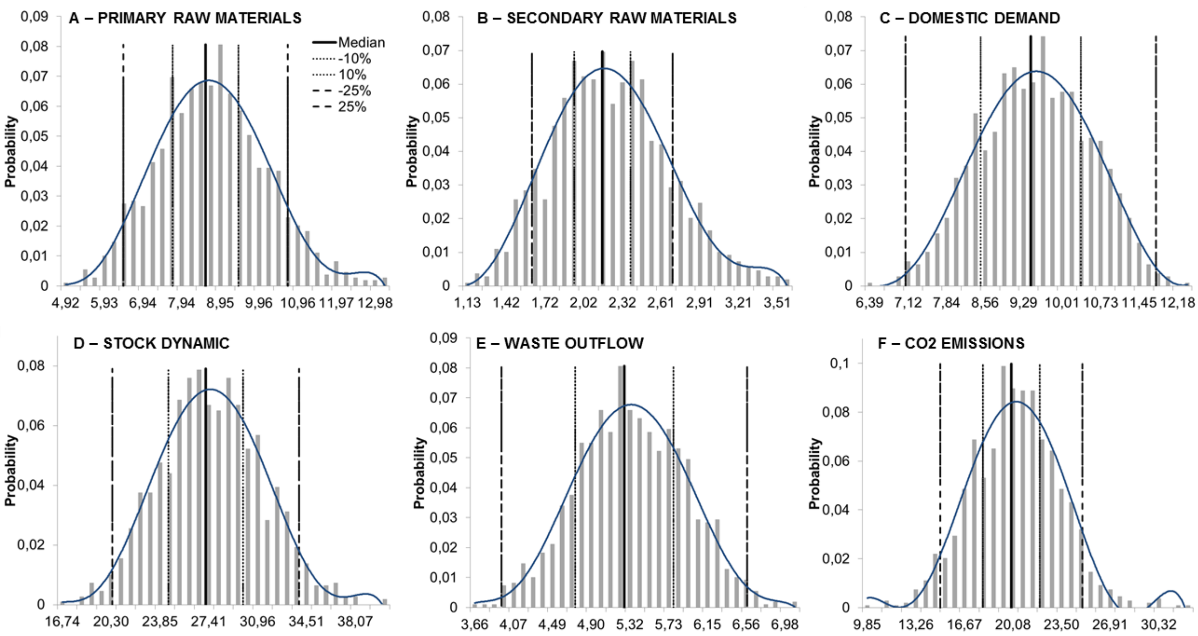


Figure 58: Results for output factor from a Monte Carlo simulation for plastic products

## B.3. Quantitative Sensitivity Analysis

QSA are often performed using multiple linear regression techniques. For each of the selected outputs a multi-variable linear regression was made. For some cases such as paper the number of variables was 16, while for plastics and wood the number increased to 24, as shown in table B.1. P-value lower that 0.05 are statistically significant in the changes of the input variable. In other words, a predictor that has a low p-value is likely to be a meaningful addition to your model because changes in the predictor's value are related to changes in the response variable.

If it is greater than 0.05 then it is not statistically significant. The regression coefficients describe the fractional change of the standard deviation of the output, when the *ith* input is changed by one standard deviation. For example, if the standardized regression coefficient is $\Gamma_i = 0.25$ and the output standard deviation is $\sigma_y = 10$ while the input factor $x$ has $\sigma_x = 2$, then by changing $x$ by 2 units the output result will change by 4 units ($\Gamma_i \times \sigma_y$). Further, the direction of the effect is given by the sign of the coefficients. A main drawback of linear regression analysis is their poor performance by non-linear models and can mislead conclusions. Thus, with the fit of the least squares between the dependent and independent variables (that is, $R^2$ or R-Squared), the regression linearity can be checked. Further, the reliability of the regression to do future estimations of the output variable is also estimated. An acceptable fit begin when its value is over 0.7, where 1.0 is a perfect fit.

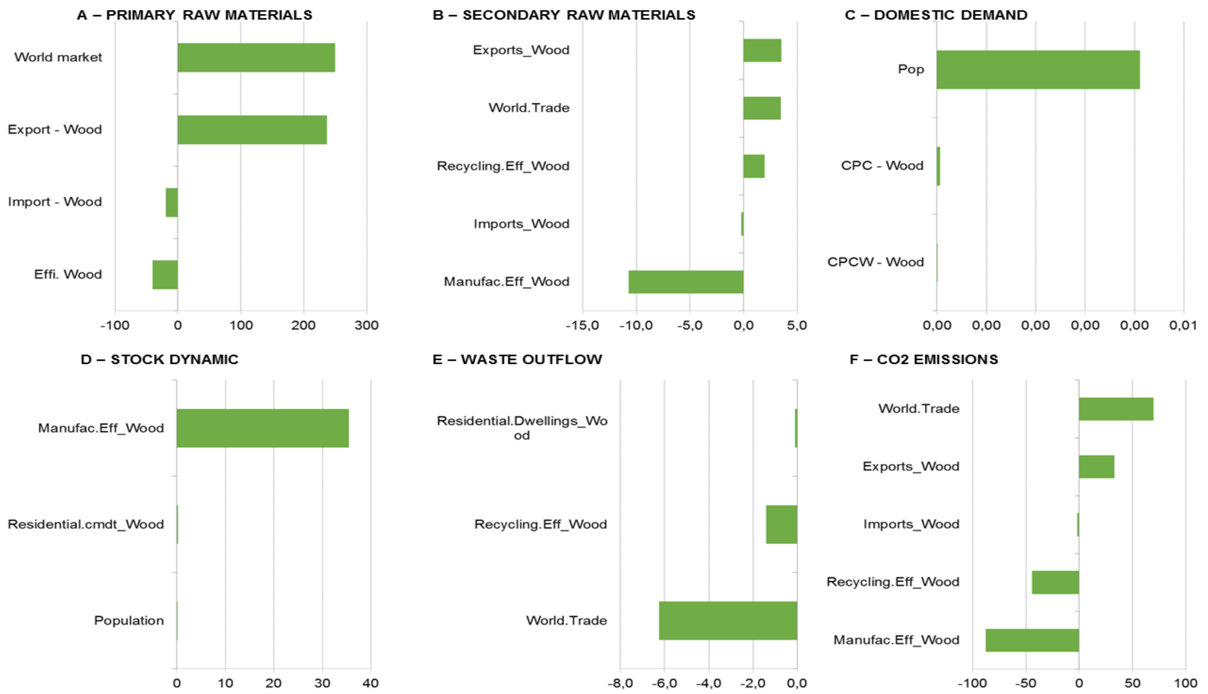


Figure 59: Variation of standardized linear regression coefficients of input variables for sensitivity analysis on wood products

The SRC shown in figures B.3-A to F and figures B.4-A to F, describe the input variables with larger effects over the six selected output factors for wood and plastic material groups. For instance, the German world market share $\Gamma_{TW}$ is one of the most sensitive variables for at least six of the evaluated output factors. This variable plays a fundamental role in the estimation of the exported goods and in the mass balance of the system. Concerning the goal of the model, which is not centered on the estimation of foreign trade flows, a simplification and reduction of the uncertainty of the outputs of the model can be made, based on the balancing properties of foreign trade. In other words, and as seen in several economical models, either exports or imports become a dependent variable of the other. For Germany, for instance, the exporting characteristic of its economy can be used as regulating parameter based on imports information. While this was not initially programmed in the model it is a suggestion for a further refurbishment. Imports and export flows $\Gamma_{TI}$ and $\Gamma_{TE}$, correspondingly, as well as the manufacturing and recycling efficiencies $\Gamma_{ME}$ and $\Gamma_{RE}$, respectively, have also shown a strong correlation with the output variables.

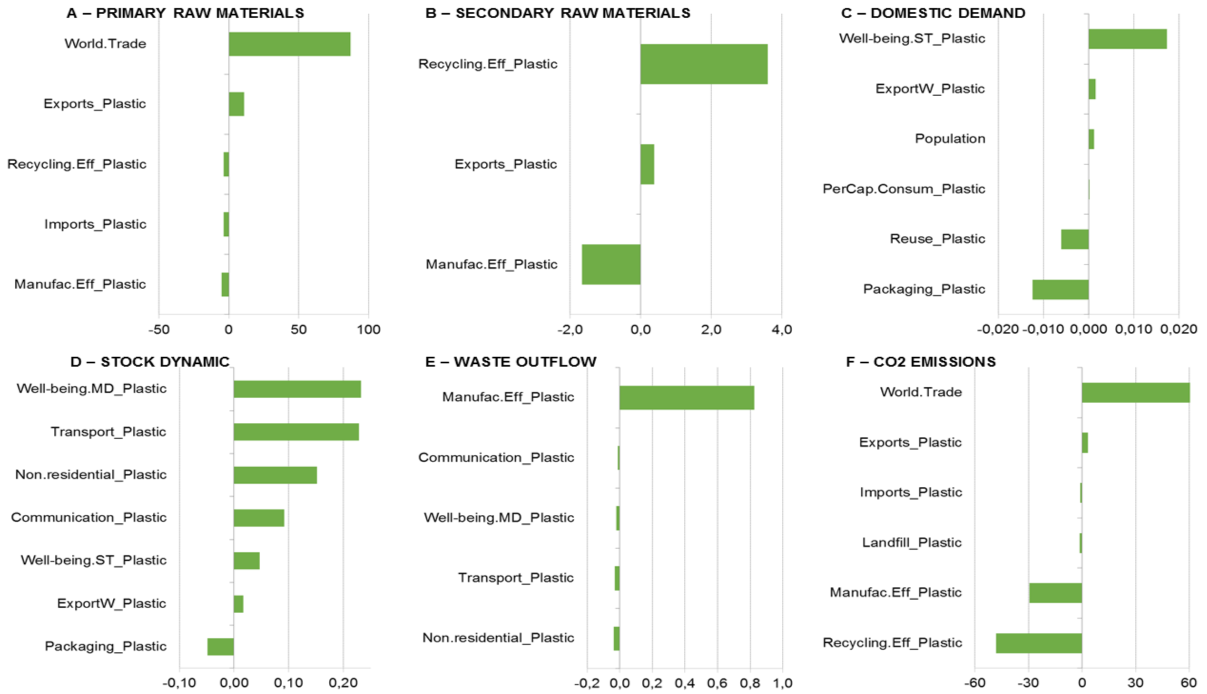


Figure 60: Variation of standardized linear regression coefficients of input variables for sensitivity analysis on plastic products

Table 19: Input model variables used for sensitivity analysis

| Description | Lower value | Mean value | Higher value |
|---|---|---|---|
| Per capita consumption (kg/cap) | | | |
| Paper - Domestic | 200 | 251 | 330 |
| Wood - Domestic | 350 | 440 | 520 |
| Plastic - Domestic | 85 | 120 | 150 |
| Paper - Global | 40 | 56 | 75 |
| Wood - Global | 180 | 285 | 380 |
| Plastic - Global | 25 | 45 | 65 |
| Population change | | | |
| Germany (Mio.) | 70.9 | 82.2 | 86.1 |
| Global[a] | 81.2 | 81.7 | 83.2 |
| Manufacturing efficiency (%) | | | |
| Paper | 0.85 | 0.95 | 0.99 |
| Wood | 0.90 | 0.92 | 0.99 |
| Plastic | 0.85 | 0.93 | 0.99 |
| Recycling efficiency[b] (%) | | | |
| Paper | 0.85 | 0.95 | 0.99 |
| Wood | 0.85 | 0.95 | 0.99 |
| Plastic | 0.85 | 0.95 | 0.99 |
| Foreign Trade | | | |
| German world market share (%) | 5.50%[c] | 7.72% | 11.0% |
| Paper - Export | 0.20 | 0.47 | 0.80 |

Table B.1 (continuation): Input model variables used for sensitivity analysis

| Description | Lower value | Mean value | Higher value |
|---|---|---|---|
| Wood - Export | 0.02 | 0.05 | 0.09 |
| Plastic - Export | 0.05 | 0.12 | 0.28 |
| Paper - Import | 0.25 | 0.55 | 0.80 |
| Wood- Import | 0.18 | 0.35 | 0.45 |
| Plastic- Import | 0.02 | 0.11 | 0.40 |
| Waste management processes | | | |
| Paper - Recycling[d] | 0.95 | 1.05 | 1.50 |
| Wood - Recycling[d] | 0.40 | 0.50 | 3.00 |
| Plastic - Recycling[d] | 1.0 | 3.50 | 6.0 |
| Paper - Reuse | 0 | 0.25 | 5.0 |
| Wood - Reuse | 0 | 0.25 | 2.0 |
| Plastic - Reuse | 0 | 0.25 | 3.0 |
| Paper - Landfill | -1.0 | -1.0 | 0.3 |
| Wood - Landfill | -1.0 | -1.0 | 2.0 |
| Plastic - Landfill | -1.0 | -1.0 | 0.3 |
| Service-based lifetime change[e] | | | |
| Paper - Packaging | 0.5 | 1.0 | 2.5 |
| Wood - Packaging | 0.5 | 1.0 | 2.5 |
| Plastic - Packaging | 0.5 | 1.0 | 2.5 |
| Paper - Well-being | 0.5 | 1.0 | 2.5 |
| Wood - Well-being | 0.5 | 1.0 | 2.5 |
| Plastic - Well-being | 0.5 | 1.0 | 2.5 |
| Paper - Communication | 0.5 | 1.0 | 2.0 |
| Plastic - Communication | 0.5 | 1.0 | 2.5 |
| Plastic - Transport | 0.5 | 1.0 | 2.5 |
| Wood - Non-residential commodities | 0.5 | 1.0 | 2.0 |
| Plastic- Non-residential commodities | 0.5 | 1.0 | 2.0 |
| Wood - Residential commodities | 0.5 | 1.0 | 2.0 |
| Plastic - Residential commodities | 0.5 | 1.0 | 2.0 |
| Wood - Non-residential dwellings | 0.5 | 1.0 | 1.5 |
| Plastic - Non-residential dwellings | 0.5 | 1.0 | 1.5 |
| Wood - Residential dwellings | 0.5 | 1.0 | 1.5 |
| Plastic - Residential dwellings | 0.5 | 1.0 | 1.5 |

*Comments:* a) Linear regression slope value; b) Fraction of recycled materials during recycling process; c) WTO, 2015; d) Includes exported fraction; e) n-fold change

Table 20: Output factor variability based on Monte Carlo simulation per material group

| | Output factor, Mt/a | Median | 1st-deciles | 1st-quartiles | Skewness | Kurtosis |
|---|---|---|---|---|---|---|
| Paper | | | | | | |
| P-1 | Primary raw material use | 7.7 | 23.4% | 50.3% | 0.57 | -1.06 |
| P-2 | Secondary raw material use | 11.6 | 66.8% | 96.3% | 0.5 | -1.12 |
| P-3 | Domestic demand | 19.8 | 70.0% | 98.4% | 0.27 | -1.42 |
| P-4 | Stock building | 19.5 | 28.8% | 60.2% | 0.53 | -1.24 |
| P-5 | Waste outflow | 16.4 | 69.6% | 98.5% | 0.34 | -1.33 |
| P-6 | $CO_2$-Emissions | 19.1 | 58.2% | 93.4% | 0.52 | -1.17 |
| Wood | | | | | | |
| W-1 | Primary raw material use | 29.85 | 72.2% | 96.4% | 0.73 | -0.92 |

Table B.2 (continuation): Output factor variability based on Monte Carlo simulation per material group

| | Output factor, Mt/a | Median | 1st-deciles | 1st-quartiles | Skewness | Kurtosis |
|---|---|---|---|---|---|---|
| W-2 | Secondary raw material use | 1.69 | 69.1% | 97.0% | 0.75 | -1.12 |
| W-3 | Domestic demand | 34.8 | 84.5% | 99.8% | 0.49 | -1.11 |
| W-4 | Stock building | 129.5 | 88.8% | 99.1% | 0.46 | -1.20 |
| W-5 | Waste outflow | 0.06 | 56.0% | 63.9% | 5.17 | 28,38 |
| W-6 | $CO_2$-Emissions | 42.92 | 79.5% | 99.6% | 0.69 | -0.99 |
| Plastic | | | | | | |
| K-1 | Primary raw material use | 8.56 | 53.1% | 89.1% | 0.47 | -1.17 |
| K-2 | Secondary raw material use | 2.16 | 44.1% | 81.0% | 0.38 | -1.36 |
| K-3 | Domestic demand | 9.41 | 67.3% | 99.2% | 0.21 | -1.43 |
| K-4 | Stock building | 27.17 | 59.0% | 94.3% | 0.52 | -1.22 |
| K-5 | Waste outflow | 5.25 | 65.2% | 98.8% | 0.38 | -1.34 |
| K-6 | $CO_2$-Emissions | 19.9 | 55.3% | 92.9% | 0.84 | -0.71 |

*Comments:* In a normal distribution the skewness and the corrected kurtosis (or excess) is zero.

Table 21: Results of the sensitivity analysis of output factors based on Standardized Regression Coefficients (SRC, $\Gamma x^{a}$)

| Output | $\Gamma_{CD}$ | $\Gamma_{CG}$ | $\Gamma_{P}$ | $\Gamma_{PW}$ | $\Gamma_{ME}$ | $\Gamma_{RE}$ | $\Gamma_{TW}$ | $\Gamma_{TE}$ | $\Gamma_{TI}$ | $\Gamma_{WR}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Primary raw materials use (Mt/a) | | | | | | | | | | |
| Paper | – | – | – | 0.35 | -15.4 | -21.0 | 333.5 | 5.12 | -5.56 | -1.49 |
| Wood | <0.01 | <0.01 | <0.01 | 0.19 | -40.2 | – | 249.9 | 236.5 | -19.5 | -0.03 |
| Plastic | <0.01 | <0.01 | <0.01 | 0.08 | -5.35 | -3.66 | 87.1 | 10.77 | -3.96 | -0.01 |
| Secondary raw materials use (Mt/a) | | | | | | | | | | |
| Paper | – | – | <0.01[b] | – | -3.68 | 15.42 | – | – | – | 1.60 |
| Wood | <0.01 | – | <0.01 | <0.01 | 0.02 | 1.94 | 3.45 | 3.52 | -0.23 | – |
| Plastic | <0.01 | <0.01 | <0.01 | <0.01 | -1.67 | 3.60 | – | 0.38 | – | 0.01 |
| Domestic demand (Mt/a) | | | | | | | | | | |
| Paper | – | – | <0.01 | – | – | – | – | – | – | – |
| Wood | <0.01 | <0.01 | <0.01 | – | – | – | – | – | – | – |
| Plastic | <0.01 | – | <0.01 | – | – | – | – | – | – | – |
| Per service stock building (Mt) | | | | | | | | | | |
| Paper | – | – | <0.01 | – | – | – | – | – | – | – |
| Wood | <0.01 | <0.01 | 0.01 | – | 35.48 | – | – | – | – | – |
| Plastic | <0.01 | – | <0.01 | – | – | – | – | – | – | – |
| Paper - Packaging | <0.01 | – | <0.01 | – | – | – | – | – | – | – |
| Plastic - Packaging | <0.01 | – | <0.01 | – | – | – | – | – | – | – |
| Paper - Communication | – | – | <0.01 | – | – | – | – | – | – | – |
| Plastic - Communication | <0.01 | – | <0.01 | – | – | – | 10.95 | – | – | – |
| Wood - Well being | <0.01 | <0.01 | <0.01 | – | – | – | – | – | – | – |
| Plastic - Well being | <0.01 | – | <0.01 | – | – | – | 23.37 | – | – | – |
| Plastic - Transport | <0.01 | – | <0.01 | – | – | – | 9.60 | – | – | – |
| Wood - Dwellings - Residential | <0.01 | <0.01 | 0.01 | – | 37.30 | – | 43.17 | – | – | – |
| Plastic - Dwellings - Non-residential | <0.01 | – | <0.01 | – | 3.30 | – | – | – | – | – |
| Waste outflow (Mt/a) | | | | | | | | | | |
| Paper | <0.01 | – | <0.01 | – | – | – | – | – | – | – |
| Wood | – | – | – | – | – | -1.41 | -6.25 | – | – | – |
| Plastic | <0.01 | – | <0.01 | – | 0.83 | – | – | – | – | – |
| Paper - Packaging | <0.01 | – | <0.01 | – | – | – | – | – | – | – |
| Plastic - Packaging | <0.01 | – | <0.01 | – | – | – | – | – | – | – |
| Paper - Communication | <0.01 | – | <0.01 | – | – | – | – | – | – | – |
| Plastic - Communication | <0.01 | – | <0.01 | – | – | – | – | – | – | – |
| Wood - Well being | – | – | – | – | – | – | – | – | – | – |
| Plastic - Well being | <0.01 | – | <0.01 | – | – | – | – | – | – | – |
| Plastic - Transport | <0.01 | – | <0.01 | – | – | – | – | – | – | – |
| Wood - Dwellings - Residential | – | – | – | – | – | -0.89 | -4.16 | – | – | – |
| Plastic - Dwellings - Non-residential | – | – | – | – | – | – | – | – | – | – |
| Carbon emissions (Mt/a) | | | | | | | | | | |
| Paper | – | – | <0.01 | 0.08 | -30.7 | -45.0 | 69.07 | 0.58 | -0.71 | -2.52 |
| Wood | <0.01 | <0.01 | <0.01 | 0.07 | -87.5 | -44.5 | 69.91 | 33.18 | -1.73 | -0.04 |
| Plastic | <0.01 | – | <0.01 | 0.09 | -29.5 | -48.2 | 61.45 | 3.27 | -1.20 | -0.03 |
| Paper - Post-consumer waste | – | – | – | – | – | – | – | -0.29 | – | -3.02 |
| Wood - Post-consumer waste | <0.01 | – | <0.01 | – | – | – | – | – | – | -0.04 |
| Plastic - Post-consumer waste | <0.01 | <0.01 | <0.01 | – | – | – | – | – | – | -0.03 |
| Paper - Post-industrial waste | – | – | – | 0.07 | -31.14 | -45.51 | 78.49 | 0.55 | -0.67 | 0.36 |
| Wood - Post-industrial waste | <0.01 | <0.01 | <0.01 | 0.06 | -41.9 | -88.4 | 70.37 | 22.96 | -1.89 | 9 |
| Plastic - Post-industrial waste | <0.01 | – | <0.01 | 0.07 | -28.4 | -44.3 | 71.14 | 1.94 | -0.97 | <0.01 |
| Paper - Landfilled waste | – | – | – | 0.02 | – | – | – | – | – | – |
| Wood - Landfilled waste | – | – | <0.01 | – | – | – | – | – | – | – |
| Plastic - Landfilled waste | – | – | <0.01 | – | – | – | – | 1.58 | – | – |

Comments: CD = Consumption Domestic; CG = Consumption Global; P = Population; PW = Population Global; ME = Manufacturing Efficiency; RE = Recycling Efficiency; TW = German Global Trade; TE = Exports; TI = Imports; WR = Recycling; a)x represents the input variables shown in table B.1; b)values between -0.01 < x < 0.01

Table B.3 (continuation): Results of the sensitivity analysis of output factors based on Standardized Regression Coefficients (SRC, $\Gamma x$[a])

| Output | $\Gamma_{WU}$ | $\Gamma_{WL}$ | $\Gamma_{SP}$ | $\Gamma_{SW}$ | $\Gamma_{SC}$ | $\Gamma_{ST}$ | $\Gamma_{SRC}$ | $\Gamma_{SND}$ | $\Gamma_{SRD}$ | $R^2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Primary raw materials use (Mt/a) | | | | | | | | | | |
| Paper | – | – | – | – | 0.09 | – | – | – | – | 0.81 |
| Wood | – | 0.02 | – | 0.06 | – | – | 0.09 | – | – | 0.80[c] |
| Plastic | – | – | – | 0.02 | – | – | – | – | – | 0.78[c] |
| Secondary raw materials use (Mt/a) | | | | | | | | | | |
| Paper | <0.01 | -0.07 | – | – | 0.09 | – | – | – | – | 0.84 |
| Wood | <0.01 | – | – | – | – | – | <0.01 | – | -0.02 | 0.64[c] |
| Plastic | <0.01 | -0.02 | – | – | – | <0.01 | – | – | -0.03 | 0.78[c] |
| Domestic demand (Mt/a) | | | | | | | | | | |
| Paper | <0.01 | – | – | – | 0.01 | – | – | – | – | 0.84 |
| Wood | – | – | – | – | – | – | – | – | – | 0.79[c] |
| Plastic | -0.01 | – | -0.02 | 0.02 | – | – | – | – | – | 0.82[c] |
| Per service stock building (Mt) | | | | | | | | | | |
| Paper | -0.02 | – | 0.07 | 0.09 | 2.23 | – | – | – | – | 0.77 |
| Wood | – | – | – | – | – | – | 0.28 | – | 0.78c | |
| Plastic | – | – | -0.04 | 0.23 | 0.09 | 0.23 | – | 0.15 | – | 0.44[c] |
| Paper - Packaging | <0.01 | – | 0.03 | 0.04 | 0.95 | – | – | – | – | 0.77 |
| Plastic - Packaging | – | – | – | – | – | – | – | – | – | 0.05[c] |
| Paper - Communication | <0.01 | – | 0.04 | 0.05 | 1.28 | – | – | – | – | 0.77 |
| Plastic - Communication | – | – | -0.01 | 0.06 | 0.02 | 0.06 | – | 0.05 | – | 0.31 |
| Wood - Well being | – | – | – | – | – | – | 0.11 | – | 0.14 | 0.76[c] |
| Plastic - Well being | – | – | -0.02 | 0.12 | 0.05 | 0.13 | – | 0.11 | – | 0.31[c] |
| Plastic - Transport | – | – | <0.01 | 0.05 | 0.02 | 0.05 | – | 0.04 | – | 0.32[c] |
| Wood - Dwellings - Residential | – | – | – | – | – | – | 0.16 | – | 0.36 | 0.77[c] |
| Plastic - Dwellings - Non-residential | – | – | – | 0.01 | – | – | – | – | – | 0.83[c] |
| Waste outflow (Mt/a) | | | | | | | | | | |
| Paper | <0.01 | – | – | – | 0.12 | – | – | – | – | 0.83 |
| Wood | – | – | – | – | – | – | -0.05 | – | -0.10 | 0.26[d] |
| Plastic | <0.01 | – | – | -0.02 | -0.01 | -0.03 | – | -0.04 | – | 0.71[c] |
| Paper - Packaging | <0.01 | – | – | – | 0.09 | – | – | – | – | 0.83 |
| Plastic - Packaging | <0.01 | – | <0.01 | <0.01 | – | – | – | – | – | 0.81[c] |
| Paper - Communication | <0.01 | – | – | – | 0.07 | – | – | – | – | 0.83 |
| Plastic - Communication | – | – | – | <0.01 | <0.01 | <0.01 | – | <0.01 | – | 0.37 |
| Wood - Well being | – | – | – | – | – | – | -0.02 | <0.01 | -0.05 | 0.24[d] |
| Plastic - Well being | – | – | – | -0.01 | <0.01 | -0.01 | – | -0.01 | – | 0.37[c] |
| Plastic - Transport | – | – | – | <0.01 | <0.01 | <0.01 | – | <0.01 | – | 0.37[c] |
| Wood - Dwellings - Residential | – | – | – | – | – | – | -0.02 | – | -0.04 | 0.33[d] |
| Plastic - Dwellings - Non-residential | – | – | <0.01 | <0.01 | – | – | – | – | <0.01 | 0.01 |
| Carbon emissions (Mt/a) | | | | | | | | | | |
| Paper | -0.02 | -0.87 | – | – | 0.09 | – | – | – | – | 0.60 |
| Wood | -0.04 | – | -0.05 | – | – | – | – | – | – | 0.52 |
| Plastic | – | -1.31 | – | – | – | -0.05 | – | – | – | 0.46[c] |
| Paper - Post-consumer waste | -0.01 | -2.16 | 0.02 | 0.02 | 0.05 | – | – | – | – | 0.81 |
| Wood - Post-consumer waste | -0.03 | -0.08 | – | – | – | – | – | – | – | 0.78[c] |
| Plastic - Post-consumer waste | -0.01 | -1.27 | – | -0.03 | – | -0.05 | – | – | 0.09 | 0.85 |
| Paper - Post-industrial waste | <0.01 | – | – | – | 0.05 | – | – | – | – | 0.43 |
| Wood - Post-industrial waste | – | – | -0.03 | – | – | – | – | 0.09 | – | 0.40[c] |
| Plastic - Post-industrial waste | – | – | – | 0.02 | – | – | – | – | – | 0.37[c] |
| Paper - Landfilled waste | – | 1.30 | -0.01 | -0.01 | – | – | – | – | – | 0.72 |
| Wood - Landfilled waste | – | 0.08 | -0.03 | – | – | – | -0.05 | – | – | 0.07 |
| Plastic - Landfilled waste | – | – | – | – | – | – | – | – | – | 0.01 |

Comments: WU = Reuse; WL = Landfill; SP = Service Packaging; SW = Service Well-being; SC = Service Communication; ST = Service Transport; SNC = Service Non-residential Commodities; SND = Service Non-residential Dwellings; SRD = Service Residential Dwellings; a)x represents the input variables shown in table B.1; c)excluding service-based variables; d)considering only service-based variables

## Annex C: Step-wise procedure for using the EW-SFM in Excel

The modeling of the anthropogenic material system in Germany is performed on an Excel-based model including the use of macros. Because of the complexity and multiple information feeding channels, the model has several linked files with and without VBA programming (macros) with various spreadsheets that supply or retrieve information for the calculation process. Table C.1 summarize the Excel files used for the dynamic modeling. The "Links" column provides the retrieved files.

### C.1. Initial conditions

The initial conditions set the standard or default values for the dynamic modeling. When the modeling files are open, data from the following files are retrieved: "Percapitaconsumption-regressions.xlsm", "Stock services.xlsm" and "Composition-Product-groups.xls". The first file provides the information found in figure A.1 in Annex A used for the calculation of the domestic demand. The second file provides information about the distribution of the services in the annual market share considering changes in the distribution. This means that the possibility of varying the final market share of the services affects the whole service distribution. With an iterative process, the annual growth (or degrowth) rates are calculated. These values are used for the estimation of the domestic per capita consumption. The third file provides information about the composition of the product groups in terms of processed raw materials. This information is used to estimate the total required raw material per year.

As seen the complete modeling period is composed of three coupled files that cover the time period between 1929 and 2055. The model was split in three modules, to reduce the instability of the software and to accelerate the modeling time. Therefore, the model can be divided in two modeling processes. The first estimates all the historic information based on time-series or calculated data regression between 1929 and 2014. The year 2014 becomes the final period of the historic part of the model. From 2015 on, the scenario approach part estimates the behavior of evaluated variables in the anthropogenic material system until 2055.

#### C.1.1. Check list

**Determination of per capita consumption of material groups**

Considering the lack of historic data in some periods, it was determined to make a mathematical regression of the per capita consumption of each material group at national and world level to obtain data for the dynamic model. To define the per capita consumption of the materials at domestic and world level, data from statistical databases, industry, reports or international institutions (FAO) were used. Multiple sources often give different values of the consumption. In this case, an average value of the reports is assumed.

In file "Percapitaconsumption-regressions.xlsm" the historical available time-series are included. Using the values of 2014 the per capita consumption of 2060 is estimated, based on economic and consumption projections of the related industries. Once these values are determined logistical regressions are performed for the whole modeling period.

### Definition of the market share change

The market share of products is has a slow dynamic determined mainly by the consumption patterns, the changing technologies or the increase of some services. Based on consumption data the market share for 1930, 2014 and 2055 were estimated. These three points direct the change of the market along the simulation. Available data were used (mostly for the values of 2014) and assumptions or individual information were used for complementing the lacking values of the other years. The model considers each material group as an individual market. Thus, each material group has its own dynamic.

In file "Stocks services.xlsm" the expected variations of the market are given. For example the reduction of paper for communication, or the change in amount of materials used for capital goods in Germany and are iterated to define an annual market change. This value is then used in the model to estimate each year.

### Adjustment of per capita consumption per service

As mentioned above, the per capita consumption for the initial calculation is based on a logistic regression, but might change after 2015. This means that until year 2014 all scenarios have the same per capita consumption values, and from 2015 the per capita consumption for the alternative scenarios is estimated with linear regressions. This is performed to have a consistent scenario approach and to avoid unreal behavior in the future period caused by a logistic curve. It is clear that a change in the final value of the per capita consumption, and market shares will affect the value of 2015. Thus, in file "Model-Scenario-X.xlsm" in sheet "Scenario" the per capita consumption is compared to the initial baseline results to match the corresponding changes. Iteration is then performed to estimate the linear coefficients of each service.

## C.1.2. Modeling options

### Market share per services

The model has information about the market shares for historic periods. In order to estimate the future market shares, the user must define or estimate a potential change compared to the basis year. In the file “Stock services.xlsm” it is possible to estimate then the annual rates in order to achieve the desired final market shares.

### Reuse or refuse of goods

As an option, the change of in-use lifetime values represent a mathematical change in the in-use consumption pattern, namely reuse or refuse of final goods. In file Model-Scenario-X.xlsm" in sheet "Cockpit" a table for variation of the in-use lifetime is presented, which increases in percent according to the standard in-use values.

## Population dynamics

Population dynamics has been retrieved from statistical databases DESTATIS and FAOSTAT for the German and world population, respectively. From the sensitivity analysis it was concluded that population is a very strong driver of the anthropogenic material system. In desired, changes in the population developments are taken from projections from DESTATIS or FAOSTAT. This are not estimated within the model.

## Manufacturing efficiencies

For the scenario approach the modification of overall manufacturing efficiencies per material group are available. These values are estimated from current or state-of-the-art data (Mantau et al., 2010b; Consultic, 2013; Hashimoto et al., 2004) for the baseline scenario.

## Final remarks

Once all the desired changes have been made, it is recommended to close all the Excel sheets, except Model-Scenario-X.xlsm". The button "Calculate" initiates the modeling calculation. Check that all other files beside the scenario are closed.

Table 22: List of Excel files used for the modeling of anthropogenic material systems

| File name | Type | Purpose | Links |
|---|---|---|---|
| Modeling files | | | |
| Model-1929-1971i.xlxm | VBA | Models AMS between 1929-1971 | Product-groups.xlsx, Percapitaconsumption-regressions.xlsm, Stock services.xlsm |
| Model-1972-2014i.xlxm | VBA | Models AMS between 1972-2014 | Model-1929-1971i.xlxm, Composition-Product-groups.xlsx, Percapitaconsumption-regressions.xlsm, Stock services.xlsm |
| Model-Scenario-Base.xlxm | VBA | Defines the standard AMS | Model-1972-2014i.xlxm |
| Model-Scenario-behavior-all.xlxm | VBA | Models Reuse scenario | Model-1972-2014i.xlxm |
| Model-Scenario-circularity.xlxm | VBA | Models Circularity scenario | Model-1972-2014i.xlxm |
| Model-Scenario-foreign.xlxm | VBA | Models Foreign scenario | Model-1972-2014i.xlxm |
| Model-Scenario-konsum.xlxm | VBA | Models Refuse scenario | Model-1972-2014i.xlxm |
| Model-Scenario-recycling.xlxm | VBA | Models Recycling scenario | Model-1972-2014i.xlxm |
| Model-Scenario-substipla4pap.xlxm | VBA | Models Substitution Plastic scenario | Model-1972-2014i.xlxm |
| Model-Scenario-substipla4papG.xlxm | VBA | Models Substitution Plastic + scenario | Model-1972-2014i.xlxm |
| Information files | | | |
| Composition-Product-groups.xlsx | – | Estimates product group material composition | – |
| Percapitaconsumption-regressions.xlsm | VBA | Defines per capita consumption for all carbon-based materials | – |
| Stock services.xlsm | VBA | Estimates market shares per services | – |
| Results-1929-2055-Base.xlsx | – | Compiles results from Baseline scenario | Model-Scenario-Base.xlxm |
| Results-1929-2055-behavior-all.xlsx | – | Compiles results from Reuse scenario | Model-Scenario-Behavior.xlxm |
| Results-1929-2055-circularity.xlsx | – | Compiles results from Circularity scenario | Model-Scenario-Circularity.xlxm |
| Results-1929-2055-foreign.xlsx | – | Compiles results from Foreign scenario | Model-Scenario-Foreign.xlxm |
| Results-1929-2055-konsum.xlsx | – | Compiles results from Refuse scenario | Model-Scenario-Konsum.xlxm |
| Results-1929-2055-recycling-all.xlsx | – | Compiles results from Recy cling scenario | Model- Scenario-Recycling.xlxm |
| Results-1929-2055-substipla4pap.xlsx | – | Compiles results from Sub stitution Plastic scenario | Model- Scenario-Substipla4pap.xlxm |
| Results-1929-2055-substipla4papG.xlsx | – | Compiles results from Sub-stitution Plastic + scenario | Model- Scenario-Substipap4pla.xlxm |
| Results-compilation-scenarios.xlsx | – | Compiles results from all scenarios | All the “Results-1929-2055”- type files |

*Comments:* VBA: Programming with macros; AMS: Anthropogenic Material System