

How TNO is supporting manufacturers in their journey toward a circular future



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This insight paper is intended for both policy makers and SMEs to provide insight into the efforts, challenges, lessons and results of both the European Commission and TNO to increase the sustainability of the (high-tech) manufacturing industry in Europe.

In the journey towards a more sustainable future, European governments are exploring different ways to support European manufacturers to become more sustainable¹. One approach to becoming more sustainable is circularity: designing products and processes in such a way to support (among others) the reuse, recycle and repair of products and their (raw) materials. This is in contrast with the traditional lifecycle of producing products (using them and then throwing them away). From a sustainability perspective it seems obvious that design and production processes increasingly need to be shifted towards this circular approach to establish a circular economy where “products and materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting.”² Additionally,

it is important to note that a European industry that becomes more circular becomes less dependent on non-EU suppliers, and thereby strengthens Europe’s strategic autonomy: circularity and strategic autonomy go hand in hand.

However, many Small and Medium-sized Enterprises (SMEs) do not know where to start to become more circular. The Horizon Europe Project called DaCapo³ aimed to address this point. In this project a total of 15 partners from all over Europe have been involved to conduct research and develop practical tools and methods that give manufacturers concrete handles, specifically focusing on SMEs in the European manufacturing industry. TNO’s role was mainly focused on developing the Agile Methodology⁴: a public deliverable and practical tool that serves as a first step for SMEs to start their journey towards becoming more circular. Other partners focused, among others on topics such as developing a network of Didactic Factories⁵ and developing “guidelines for data economy mechanisms in circular economy ecosystems”⁶.

¹ [Sustainability – Internal Market, Industry, Entrepreneurship and SMEs](#)

² [The Circular Economy | Definition & Model Explained | Ellen MacArthur Foundation](#)

³ [DaCapo](#)

⁴ [D2.4+Achieving+Circularity+in+Manufacturing+Practical+Guidance+and+Tools.pdf](#)

⁵ [D6.1 – DaCapo Didactic Factories for Manufacturing Circularity](#)

⁶ <https://static1.squarespace.com/static/6418c1a93db6245f11a935c0/t/6a4b85ce756d2d00fe0aaf21/1783334354729/Standardisation+and+data+economy+guidelines+and+recommendations.pdf>

The background: the importance of circularity for sustainability

In generic terms: we live in a take-make-dispose world. Raw materials are extracted, turned into products, used briefly, and discarded. The industrial sector accounts for approximately one-quarter of global greenhouse gas emissions^{7,8} and that is before factoring in the 62 million tons of electronic waste generated each year, less than a quarter of which is properly recycled⁹.

The description above highlights the importance of increasing the circularity of the (European) manufacturing industry to become more sustainable. That is exactly the rationale of the DaCapo project that is funded by the European Commission:

“Europe has a high level of dependence from imported materials, many of which have a great impact on its economy due to their application in high-technology products. Considering raw materials represent the largest cost for manufacturing companies in the EU, there is a clear need for improving the raw materials usage efficiency along the industrial value chains. The vision of DaCapo is to create a new paradigm of digitally enabled industrial sustainability and resilience in the EU. The DaCapo project [has focused] its efforts in defining a new set of human-centered digital tools and services for the manufacturing industry capable of boosting the application of [circular economy] principles at different phases throughout the manufacturing value chains, enhancing the circularity of industrial processes and products.”¹⁰

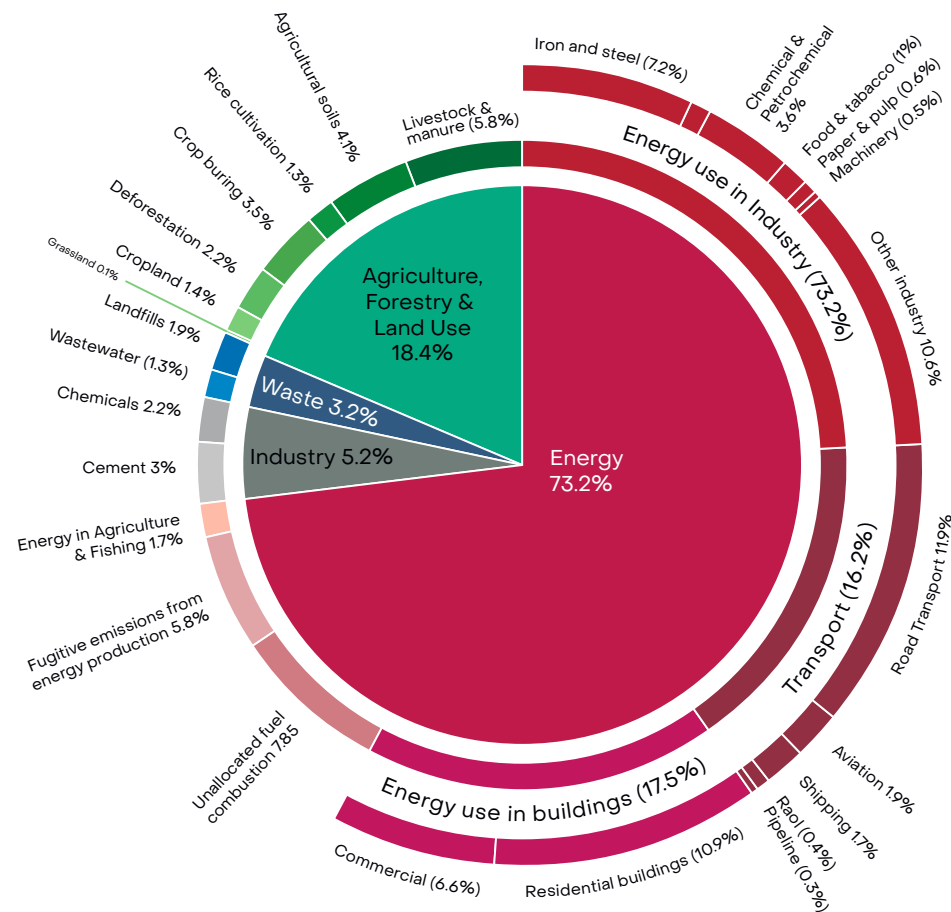


Figure 1. Energy use in Industry amounted to 24,2% of worldwide Greenhouse Gas emissions in 2016. Ritchie, H. (2020). “Sector by sector: where do global greenhouse gas emissions come from?” Our World in Data.

7 Ritchie, H., & Roser, M. (2020). “CO₂ and Greenhouse Gas Emissions”. Published online at Our World in Data <https://ourworldindata.org/ghg-emissions-by-sector>

8 IPCC (2014). Climate Change 2014: Mitigation of Climate Change. Working Group III, Chapter 10. Cambridge University Press. <https://www.ipcc.ch/report/ar5/wg3/>

9 ITU & UNITAR (2024). The Global E-waste Monitor 2024. <https://ewastemonitor.info/the-global-e-waste-monitor-2024/>

10 The Project — DaCapo

The challenge: Why circular manufacturing is not happening fast enough

European policy has set the direction but the industry itself needs to execute it. In general terms: we know that becoming more sustainable and circular requires changes, investments and comes with an unclear return on investment (ROI). And at the same time SMEs still need to have a working business model. The EU's Green Deal, Circular Economy Action Plan, and the upcoming Ecodesign for Sustainable Products Regulation, which introduces Digital Product Passports, all signal a clear ambition for sustainable production. But policy ambition and market reality are not the same thing. Becoming more sustainable may outprice an industrial partner compared to (non-EU) competitors. Hence SMEs have to be supported in their efforts to remain competitive *and* sustainable.

This is where a project such as DaCapo can provide some concrete handles: supporting SMEs in finding those business models and supporting them with concrete tools to increase the uptake of circularity practices while reducing the need of SMEs to (re)invent the wheel themselves.

The day to day life of SMEs: why circularity & strategic autonomy go hand-in-hand

In their day-to-day operations, manufacturers make decisions based primarily on financial trade-offs. When investing in circularity costs money and time with uncertain returns, it is rarely the first priority. And even if the business case does make sense (or the entrepreneurs have a certain ideological drive/goal): many SMEs lack the tools, knowledge, and bandwidth to determine where to start. There is a strategic dimension too: Circularity is not just an environmental ambition, it is an industrial resilience strategy to strengthen European strategic autonomy. Europe remains heavily dependent on critical raw materials sourced from China, Africa, and other regions, with limited European alternatives.

Structural market failures reinforce this inertia. When long-term environmental benefits must compete with short-term cost pressures, the numbers often don't add up. Even high-tech manufacturers supplying companies such as ASML rely on supply chains that Europe would like to reduce its dependency on.

Concluding: the European manufacturing industry has multiple challenges to become more sustainable and circular. First, the business case is complex (i.e. uncertain). Second, the "how/where to start" is unclear. And thirdly, we as Europe and our SMEs are still dependent on non-EU countries that provide us raw materials. So there is an urgency to support European SMEs.

DaCapo: A European mission to bridge the gap

The EU-funded DaCapo project (1010917803) was a 42-month, €5.99 million Horizon Europe collaboration with the mission to help manufacturers in Europe, particularly SMEs, to take concrete steps toward circularity. The abbreviation DaCapo comes from the title of the project: **D**igital **A**ssets and tools for **C**ircul**A**r value chains and manufacturing **P**r**O**duct.

The consortium brought together 15 partners from 10 European countries, including research and technology organizations, large industrial companies, and SMEs. For the full list please see the website of the project¹¹. The project was coordinated by AIMEN, a Spanish (technology) research center experienced in advanced manufacturing and industrial innovation.

The project centers on integrating digital technologies into traditional manufacturing processes to boost resource efficiency and reduce waste. Specifically the project has focused its research and development activities around three specific use cases from three European companies: (1) Fairphone, (2) GKN, and (3) PESMEL. In short: Fairphone develops and produces circular smartphones, GKN is a global multi-technology leader in the aerospace industry, and PESMEL is a global supplier of highly automated material handling systems.

The tools and services developed within DaCapo focus on creating new digital assets, AI-based decision support systems, and applying fairly new innovative concepts such as digital twins and digital product passports. As stated earlier: the overall aim of the project is to enhance sustainability, circularity and efficient use of raw materials across manufacturing value chains. This ranges from supply chains to production and recycling.

¹¹ [The Project — DaCapo](#).

Strengthening cross-European collaboration

Though not the core of the endeavor, the DaCapo project (similar to other Horizon Europe projects) has also strengthened the collaboration between different research and technology organizations (such as TNO), private companies (such as Fairphone) and universities (such as POLIMI) across Europe. And working across borders also means working across cultures; from Finland to Italy, from the Netherlands to Spain, from Sweden to France. This diversity in expertise and perspective is an important element that has strengthened the project: European partners contribute complementary expertise and different industrial contexts, united by a shared goal. Despite differences in language, working styles, and manufacturing traditions, the consortium has consistently found common ground. A great example of collaboration within and across Europe to increase sustainability, circularity, and thereby also European resilience.

TNO's Agile Methodology: From research to practical impact

TNO's contribution to DaCapo is grounded in a specific strength: bridging the gap between research and industry practice. As an independent research and technology organization, TNO operates at the intersection of technical knowledge and real-world application, what might be called a consultancy role within the consortium. The goal throughout the project has been to develop a solution (i.e. the agile methodology) that works for manufacturers (e.g. at the BIC in Eindhoven), with real budgets and real pressures. Not solutions that work only in theory. And additionally as a consultant to support the rest of the consortium.

TNO's overall contribution

TNO's main focus was on creating an overview of relevant business models for circularity and subsequently developing an agile methodology to help SMEs on their journey toward becoming more circular. This resulted in a practical tool that any SME can use, whether they're just starting to explore circularity or are already well along that path. Working closely with partners CEA (France) and VTT (Finland), TNO also helped develop practical tools that showed how circular a product or process really is. A big piece of this puzzle was the Digital Product Passport: essentially a digital "ID card" that follows a product throughout its life, holding key information about its materials, origin, and how it can be reused or recycled. Over the course of the

project, TNO and its partners combined their expertise to turn these concepts into concrete results — ultimately aiming to make it easier for SMEs to shift toward more circular, sustainable ways of working.

Mapping the landscape: circular business models that work

Making manufacturing circular also means rethinking not just how companies make things, but — simply put — also about how they make money (i.e. making their business model work and keeping it sustainable). The initial part of TNO's work was focused on exactly this: providing an overview of possible business models that "work" in the context of circularity. So before building concrete tools, TNO focused on creating an overview of relevant business models, to make sure that the tool TNO developed later in the project would address concerns of SMEs.

One key concept is servitization, which is defined as shifting from selling a product to selling the outcome it provides. Instead of selling a machine, a company sells uptime. Instead of selling a component, it guarantees performance. This aligns SMEs' short term financial interest directly with a long term sustainable business model, which is exactly what circularity requires. The models come in different forms: product-oriented (selling with built-in maintenance), use-oriented (leasing or renting), and result-oriented (payment based on outcomes).

The circular business models that were analysed are promising but not painless. The underlying point is crucial: for circularity to "land" (i.e. for SMEs to be attractive to even consider), there must be a business case. European goals, ambitions and specifically developed tools are not enough if the economics don't work. Hence, in DaCapo's first work package an exploratory study was conducted to map the possible business models. TNO led this broad literature review of existing circularity frameworks, the established R-strategies (reduce, reuse, recycle, and beyond), and the practical challenges manufacturers face. In parallel, the French research organization CEA developed an overview of circularity indicators.

This resulted in a public whitepaper¹² and served as direct input for the Agile Methodology as it addressed questions such as: what do we already know about circularity in manufacturing, and what do companies actually need?

¹² [D1.2 Circular business models for EU manufacturing value chains](#)

Achieving Circularity in Manufacturing

About DaCapo

About this methodology & Who is this for?

Why work on circular economy?

Where to start?



This is an interactive document, allowing you to easily navigate through the contents. You can always return to this overview through the clickable button on the top right corner of each page indicating 'back to overview'.



Chapter 1

Inspiration: Why move to a Circular Economy?

Defining Circular Economy

Circular strategies R-strategies

Circular business models

Practical tools

LLM guidance



Chapter 2

Setting your Circular Strategy & Goals

Why and how to set goals?

Step 1: Maturity, self-assessment, inefficiencies

Practical tools Step 1

Step 2: Identify opportunities

Practical tools Step 2

Step 3: Define circularity goal and business models

Practical tools Step 3

Step 4: Measure progress and adjust (agile)

Practical tools Step 4

LLM guidance



Chapter 3

Implementation & Design

Circular practices

Pre-use phase

Use phase

Closing phase

Practical tools

LLM guidance



Chapter 4

Continuing your Circular Economy Journey

What are your next steps towards circularity going to be?

DaCapo developments: what can it bring you?

Moving forwards with specialized support



Chapter 5

Customizing LLMs

What LLM models to use?

Why and how to customize LLMs

DaCapo customization script

Appendix | Click [here](#) for an overview of all practical tools provided



Achieving Circularity in Manufacturing: Practical Guidance and Tools

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Figure 2. The contents of the Agile Methodology can be used interactively and iteratively¹³.

¹³ [DaCapo agile methodology for sustainability and circularity enhancement](#)

An Agile Methodology for Any Manufacturer

The result of the aforementioned is TNO's main contribution in the DaCapo project: the development and publication of the Agile Methodology (see Figure 2 The contents of the Agile Methodology can be used interactively and iteratively): an interactive, clickable guide developed and led by TNO that helps manufacturing companies navigate their circularity journey, whatever stage they are at. It is freely available on the DaCapo project website.¹²

The methodology deliberately avoids a one-size-fits-all approach. A company just beginning to explore circularity can use it as an accessible introduction. A company already well along the path, such as Fairphone, can zoom in on specific elements of its supply chain or production process. The principle is pick and choose: depending on a company's maturity level, they can select what is useful and what to skip when something is not relevant to them.

The methodology structured across five chapters, moving from circular economy basics through strategy-setting and implementation design to practical tools and assessment methods. The final chapter covers large language models: generative AI tools that can be set up as a personalized circularity consultant, tailored to a company's products, processes, and privacy requirements¹⁴.

The methodology was developed iteratively through desk research, expert interviews with circularity consultants, workshops with DaCapo partners, and live testing of an LLM-based consultant at a consortium meeting. This was done in collaboration with [CIRCO](#), an international circular design and business innovation program that helps manufacturers redesign products, services, and business models for circularity. The methodology is designed as a tool that TNO transfers to consultancy organizations similar to CIRCO, who then use it to help their own clients in the manufacturing sector. It was also distributed directly to approximately 150–200 manufacturing companies as a stimulus to take a first step and later also through discussions at the Dutch Didactic Factory: the Brainport Industry Campus in Eindhoven, NL.

The methodology's approach to making research accessible to industry was recognized by the European Commission as an example of effective dissemination.

TNO was invited to present the Agile Methodology at a dedicated EC “Dissemination Workshop on Digital Tools for Circularity, Human Centricity and Operational Efficiency in Manufacturing”: a session specifically designed to showcase standout deliverables from Horizon Europe projects. The presentation was attended by representatives from EU-funded projects and European Digital Innovation Hubs (EDIHs) across Europe.

Circularity in Practice: Industry Use Cases

Three technology trends underpin DaCapo's approach: connectivity across manufacturing value chains, digitization of product and process data, and innovation in production techniques. Together, these make it possible to track materials and components across a product's entire lifecycle — enabling smarter decisions about repair, reuse, and resource recovery. The project translates these trends into concrete tools, tested with real companies.

Fairphone: Extending the Life of Electronics

Fairphone, the Dutch social enterprise known for its modular, repairable smartphones, is developing a battery health monitoring tool within DaCapo: a system that tracks battery condition over time and informs decisions about when and how to repair, refurbish, or recycle a device. This feeds into a broader product digital twin: a live data record of each phone that supports circular decision-making throughout its lifecycle.

Fairphone hence also serves as an example: they are currently Europe's only smartphone manufacturer, making it an example of not just of circularity, but of digital strategic autonomy. Keeping European-made electronics in circulation longer reduces dependence on imported materials and components.

“We want to make the most of the materials used in consumer electronics. We believe in a world with a closed loop; a future where e-waste is reduced thanks to long-lasting products which are continuously reused and recycled. Once resources enter our economic system, they should be kept at their highest value for as long as possible and freed for new applications once a product cannot be repaired anymore.”

¹⁴ At the time of development (in 2024) ChatGPT, Microsoft CoPilot and Claude.AI were less sophisticated than they are now in 2026. It can be interesting to “redo” this part of the Agile Methodology to explore agents and the likes to test if SMEs can increase uptake of circular practices that way. The Agile Methodology was explicitly designed as a flexible and agile tool that can be adapted over time.

GKN Aerospace: Toward Zero-Waste Production

GKN Aerospace: *“We assess the impact of our products on the environment in terms of material usage, waste, energy usage and CO₂ emissions throughout each product life cycle. By incorporating circular economy principles in our design and manufacturing processes, we are reducing our environmental impact and deliver products to end markets with increased durability and longevity and reduced waste.”*

PESMEL: Data-driven longevity

“We are committed to developing technologies that minimize environmental impact and promote sustainability. Our efforts include optimizing material use, utilizing low carbon-intensive materials, and employing energy-efficient drives with electricity regeneration. Over 90% of the materials in our systems are recyclable, and we actively support recycling, refurbishment, and waste reduction efforts.”

Other tools and contributions

Beyond the industry use cases, DaCapo has produced additional digital tools. These include among others GRETA¹⁵: developed by the University of Applied Sciences and Arts of Southern Switzerland (SUPSI¹⁶), GRETA is an AI-based decision support system that helps manufacturers evaluate circularity options for their products and processes. AIMEN contributes its expertise in laser manufacturing, robotics, and process digitalization to ensure the technologies developed are grounded in real industrial capability. Other consortium partners — including CEA, VTT, POLIMI, SUPSI, and CORE Innovation Group — bring complementary expertise in AI systems, sustainability assessment, digital twins, and other areas of technological development.

Concluding DaCapo: What comes next

DaCapo's 42-month journey has (almost) come to an end, but the transition to circular manufacturing obviously is not. The project was always designed as a catalyst, not a final destination. So what happens to the knowledge and tools it has produced?

From project to practice

Within DaCapo each consortium partner is responsible for bringing its own tools and knowledge to the market if/where applicable. For TNO that means that the deliverables (i.e. the business model analysis/review, the agile methodology, and the

whitepaper on supply chain risks) are publicly available and serve as a foundation for future work with industry clients and consultancy partners.

The methodology has already been shared with organizations such as CIRCO (a not-for-profit circularity consultancy firm) and SMEs in the Brainport Industry Campus, who can use it to make their manufacturing processes more circular.

A growing European ecosystem

DaCapo does not stand alone of course. It is part of a growing European ecosystem of initiatives that are building the infrastructure for circular manufacturing. E.g. as Digital Product Passport regulation takes effect under the Ecodesign for Sustainable Products Regulation, the frameworks and data architectures developed in DaCapo become increasingly relevant.

At TNO, this work continues on multiple fronts. In the [CIMBATT project](#), TNO is helping the battery and automotive sector prepare for the EU Battery Regulation by developing a practical battery passport: translating regulatory requirements into workable data systems for industry. In the Circular Business Program Semicon ([CBPS](#)), TNO collaborates with the Brainport Industry Campus on “re-X strategies” for lithography machines, exploring how high-value semiconductor equipment can be remanufactured, refurbished, and kept in circulation longer. And in [Rob4Green](#), a running Horizon Europe project, TNO contributes to robotic solutions for sustainable manufacturing processes.

Closer to home, within the Dutch Next Generation High Tech programme, TNO is active at the intersection of circularity and digitalization, both through autonomous factories (SI05) and connected factories (SI06). A recent [SCSN hackathon](#) explored the future of the Digital Product Passport in manufacturing supply chains, bringing together industry partners to co-create practical DPP solutions.

These projects share a common topic (or goal) with DaCapo: making circularity concrete, data-driven, and economically viable for manufacturers. The question is never just how to become more circular but how to do so in a way that creates business value. TNO's work in orchestrating ecosystems is focused on finding the common denominator between SMEs and government: connecting product data, supply chain parties, and circular strategies to help SMEs build that business case.

¹⁵ [SUPSI launches demonstration activity of its didactic Mini-Factory with the GRETA tool — DaCapo](#)

¹⁶ <https://www.supsi.ch/en>

A critical lesson learned

If there is one lesson the project reinforces, it is this: circularity cannot be an academic exercise. The manufacturing industry must be involved from day one. Not just as a target audience that receives finished tools, but as a co-creator that shapes them. Working across ten countries, across languages and cultures, DaCapo has shown that this is possible. The key is to keep talking, to meet physically, and to never lose sight of the practical problems that manufacturers face every day.

Another step towards circularity

To conclude with a final message: circular manufacturing will not scale simply because regulation requires it or because companies want to become more sustainable. Not even when regulations are enforced in a stringent manner. It scales when circularity becomes a practical business decision for four reasons: (1) when manufacturers can identify where value is lost for no good reason, (2) choose a viable circular solution that strengthens their business model, (3) obtain the necessary product and supply-chain data and (4) implement a concrete intervention. DaCapo's contribution has been to turn circularity from an abstract ambition into such an interactive decision process. If you also want to take the next step towards circularity, get in touch with us.

Laura van den Aarssen, consultant on Digital Product Passports: *"The most successful manufacturers will not implement Digital Product Passports because they have to, but because they recognize the business value they create. DPPs transform product data into a strategic asset, enabling operational excellence, stronger ecosystem collaboration, greater transparency, and new circular business models. In that sense, DPPs are not just a compliance tool, but a catalyst for industrial transformation."*

Nick Oostervink, TNO's project lead & ecosystem orchestrator: *"If we want to get circularity right across Europe, we need to think beyond national borders and industries. That means embracing differences, staying in close dialogue, and (crucially) involving the industry itself as early as possible. Otherwise we keep the risk that it remains a theoretical exercise."*

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