Achieving resilience through reconfigurability:

The role of digitisation for improved strategy and decision-making for EU manufacturing industries.

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Introduction – resilience in manufacturing policy and practice

The term resilience has regained traction in EU policy since the Covid-19 crisis and the invasion of Ukraine, ending a period of relative stability. Whereas the term *Resilience* connects to multiple disciplines and sometimes is referred to as 'black swan' events, when looking at the EU policy context, we can see that it relates mainly to national (member-state) and EU-level economic abilities to responds to global shocks. In the EU strategic agenda[1] the chosen response to a multitude of recent crises is to intensify (twin) transitions. This can be understood as the recognition that we need to understand the inter-dependence and the reinforcing factors of several transitions that need to happen simultaneously. The term resilience has been put forward in a strategic foresight report from 2020[2] in which it is defined as *'the ability not only to withstand and cope with challenges but also to undergo transitions, in a sustainable, fair, and democratic manner'*. When we look at where the term resilience is connected to EU policymaking, in the over 70.000 occurrences on the EC Search portal, recent documents relate conflicts, disaster management, financial regulations such as the upcoming DORA regulation[3], climate change and social-and economic challenges and related policy instruments. Next to recently developed Resilience Dashboards by the EC[4], there are plenty references to the Recovery and Resilience Fund (the RRF), a large fund to help countries recover post Covid-19, with one of the policy goals is for Member States and industries to become more resilient. The Joint Research Centre (JRC, the ECs in-house research centre) has introduced Resilience Dashboards to inform policymakers and the general public on external events or developments related to resilience and it provides 'readiness scores' per Member State[5]. These dashboards are divided in 4 elements: social- and economic, green, digital and geopolitical. The dashboards are based a selection of indicators that can be categorized as a capacity (enablers and/or opportunities to navigate the transitions and face future shocks) or as a vulnerability (obstacles or aspects that can worsen the negative impact of the challenges related to the green, digital, and fair transitions). Figure 1 below shows one way to measure resilience by plotting the severity of an external shock against the time a country or company or sector is exposed to that shock. The JRC has called this 'disturbance intensity' versus 'time of

[1] See EU Strategic Agenda 2019-2024

[2] 2020 Strategic Foresight Report

[3] ter Haar, J. (2022). DORA: Friend or Foe: A Qualitative Study into the Perceptions of the Financial Sector in the EU on the Expectation of the Digital Operational Resilience Act.

[4] EC resilience dashboards, see https://commission.europa.eu/strategy-and-policy/strategic-planning/strategic-foresight/2020-strategic-foresight-report/resilience-dashboards_en

[5] Darvas, Z., M. Domínguez-Jiménez, A. Devins, M. Grzegorczyk, L. Guetta-Jeanrenaud, S. Hendry, M. Hoffmann, K. Lenaerts, T. Schraepen, A. Tzaras, V. Vorsatz, P. Weil, L. Welslau, 'European Union Countries' recovery and resilience plans', Bruegel Datasets, https://www.bruegel.org/dataset/european-union-countries-recovery-and-resilience-plans

exposure'. The authors propose three different stages of resilience, by which they mean a level of readiness to deal with shocks over time. These are stability (the ability to absorb the shock), flexibility (the ability to adapt to the shock) and finally change (ability to transform).

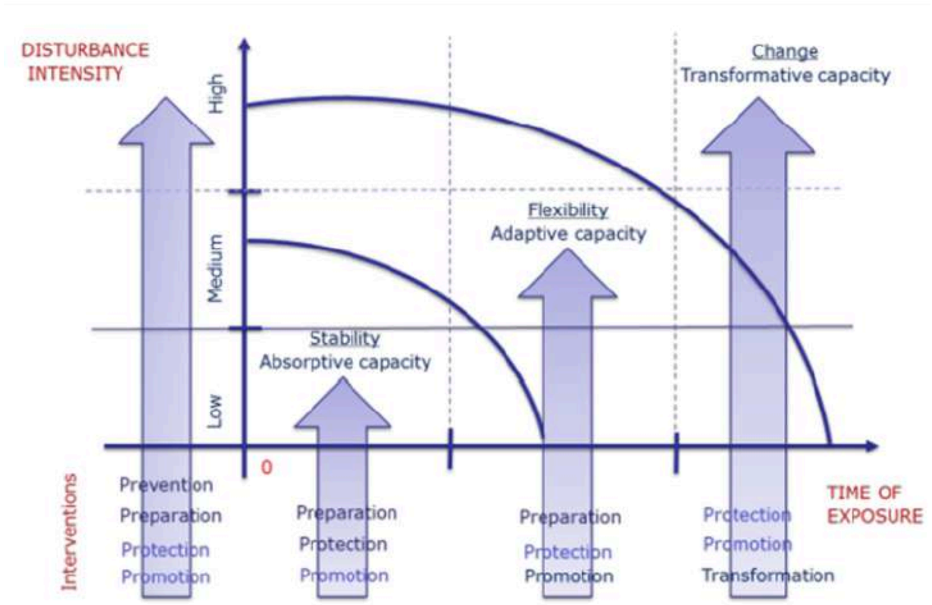


Figure 1: 3 different resilience levels. Source: Manca A; Benczur P; Giovannini E. Building a Scientific Narrative Towards a More Resilient EU Society Part 1: a Conceptual Framework . EUR 28548 EN. Luxembourg (Luxembourg): Publications Office of the European Union; 2017. JRC106265

Taking a closer look at resilience indicators in the context of digitisation of industry, we see macro- economic indicators around trade (deficits in ICT-related goods and services), indicators dealing with skills, expertise and gender balance, indicators concerning access to -and usage of- ICT infrastructure, R&D investments and e-commerce sales. Despite being developed for Member State-level analysis, the resilience self-assessment framework can serve as an inspiration for the development of a framework to measure progress in resilience in manufacturing.

External disturbances, risks and resilience for manufacturing

As resilience is comprehensive and applies to multiple disciplines, the term has also found its way in literature reflecting on manufacturing. It has become a subject of interest for supply chain- and risk management procedures. Resilience has been described in this context as the adaptive capability for both expected and unexpected events. Becoming resilient is seen as a learning process and has been conceptualized[6] as an ability or process rather than an outcome and refers to a state of adaptability rather than stability [7]. Moreover, it connects to vulnerability, as Sheffi & Rice (2005) state that “reducing vulnerability means reducing the chances of a disruption and increasing steps towards resilience”[8]. Likewise, the ‘made in Europe’ partnership refers multiple times to resilience for manufacturing in their strategic research agendas[9], stating that the research funded and performed under the partnership is aimed at *ensuring competitiveness and sustainability* , *and supporting resilient and adaptive manufacturing ecosystems able to cope with external disturbances and rising environmental and social requirements*, further on stating that *upgradable and robust manufacturing systems and plants are necessary for flexible, responsive and resilient manufacturing.* The concept of resilience is often linked to an increased readiness t due to a better understanding of various types of risks. Over the last decade, the term VUCA (Volatility, Uncertainty, Complexity, and Ambiguity) has gained traction as a way to classify external risks. Fridgeirsson et al (2021) report that VUCA first appeared as an acronym used by the U.S. Army War College in 1987 and became popular in strategic and leadership research throughout the 1990s[10]. Fridgeirsson *et al*., (2021) group the VUCA concepts as described by Bennett and Lemoine via a set of statements: *Volatility*, referring to Unstable and unpredictable resource cost and/or availability at unpredictable times and durations and expected fluctuations on resources with unknown timing, and magnitude. *Uncertainty*, referring to a lack of knowledge and unclear impact of change, but cause and effect known. *Complexity*, meaning the presence of many interconnected parts and often complex regulatory/political environments, with multiple component parts. *Ambiguity* can refer to doubt about the nature of cause and effect and the fact that little to no historical information to predict an outcome is available, making forecasting or planning difficult. A recent variation on classifying risks related to resilience strategies is that of BANI (Brittle, Anxcious, Non-linear and Incomprehensible).

[6] Matzenberger, J. (2013). A novel approach to exploring the concept of resilience and principal drivers in a learning environment. *Multicultural Education & Technology Journal*, *7*(2/3), 192-206.
[7] Ito, A., Hagström, M., Bokrantz, J., Skoogh, A., Nawcki, M., Gandhi, K., ... & Bärring, M. (2022). Improved root cause analysis supporting resilient production systems. *Journal of Manufacturing Systems*, *64*, 468-478.
[8] Paraphrased from Sohail, A. R., Ramish, A., Ali, Q., & Rehman, K. U. (2022). Supply chain resilience in VUCA world: towards a holistic approach of quality assurance and risk management. *International Journal of Management Research and Emerging Sciences*, *12*(1). See Sheffi, Y., & Rice Jr, J. B. (2005). A supply chain view of the resilient enterprise. *MIT Sloan management review*.
[9] The SRIDA can be found here: https://effra.eu/wp-content/uploads/2023/12/made_in_europe-sria.pdf
[10] Manimuthu, A., Venkatesh, V. G., Raja Sreedharan, V., & Mani, V. (2022). Modelling and analysis of artificial intelligence for commercial vehicle assembly process in VUCA world: a case study. *International Journal of Production Research*, *60*(14), 4529-4547.

When projecting the need for improved resilience strategies onto the domain of manufacturing industries, we can crystallize such risk-or disturbances and 'plot' them on an ideal-type production process to understand what can actually be done on company-, factory-, or even workstation-level to mitigate or respond to such risks. The main point of the VUCA elements therefor is to force companies or organisations to (re)think how they strategize, and how they make decisions.

Where the study by Fridgeirsson *et al*. (2021) looks at project-level, and many studies such as the Ponomarov & Holcomb (2009), Matzenberger, (2013), Parast & Subramanian (2021) and the abovementioned JRC studies look at the macro-level, we want to look at sector- and company level at resilience via the VUCA elements and mitigation strategies. In that context, another term is that of *World Class Manufacturing* (WCM). Manimuthu *et al.* (2022) state that 'the term has come to mean many things, but in this increasingly VUCA world (volatile, uncertain, complex and ambiguous) WCM has to include situational understanding so that companies can seize opportunities and react quickly to threats'[11]. Küpper et al (2022) in their study on resilience and VUCA in the context of manufacturing state that major global trends require producers to address three key strategic objectives, which their study participants confirmed as relevant to their operations:

- Strengthening operational resilience to address supply chain disruptions
- Improving responsiveness to changing customer requirements
- Pursuing sustainability targets

As manufacturing processes are highly dependent on materials or part arriving on time, and leaving on time, supply chain resilience (SCR) is another important element of resilience in manufacturing. SCR refers to a supply chain system that is prepared and ready for unforeseen events and risks or uncertainties, responds to them, and can counter them (Ribeiro & Barbosa-Povoa, 2018[12]). Supply network disruption is defined as "unplanned and unanticipated events that disrupt the normal flow of goods and materials within a supply chain." Supply chain disruptions can stem from a wide range of possibly factors, such as

[11] See Fridgeirsson, T.V., Kristjansdottir, B.H., Ingason, H.T. (2021). An Alternative Risk Assessment Routine for Decision Making; Towards a VUCA Meter to Assess the Volatility, Uncertainty, Complexity and Ambiguity of Complex Projects. In: Cuevas, R., Bodea, CN., Torres-Lima, P. (eds) Research on Project, Programme and Portfolio Management. Lecture Notes in Management and Industrial Engineering. Springer, Cham. https://doi.org/10.1007/978-3-030-60139-3_4

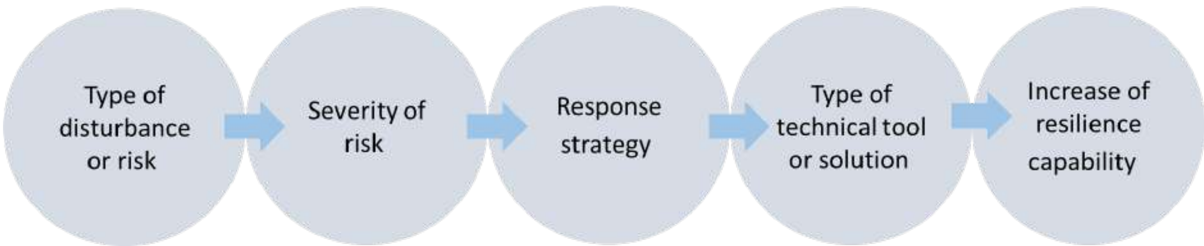
[12] Ribeiro, J. P., & Barbosa-Povoa, A. (2018). Supply Chain Resilience: Definitions and quantitative modelling approaches–A literature review. *Computers & industrial engineering*, 115, 109-122.

socio-political crises, natural catastrophes, or terrorism (Brüning et al., 2015[13]; Parast & Subramanian, 2021[14]). Being able as a manufacturing company to formulate an efficient response and to build up capability to rescue are inevitable to reduce the risks and achieve resilience (Ponomarov & Holcomb, 2009[15]). It is important to note that resilient supply chains may or may not be cost-effective in the short run, but they are more capable and effective in the long run for the business. Another recent approach to increasing resilience in the context of supply chains is 'lean supply chain management', in which logics and terminology from recent ICT start-up management are brought into the manufacturing sphere.

Ito *et al.* (2022)[16] discuss different strategies companies can adopt in facing disturbances, among which are building up capabilities of knowing what has happened and why, developing abilities to respond, to monitor and to better anticipate and learn. They continue by pointing out that '*in manufacturing companies, a commonly applied strategy for learning from past disturbances is to conduct a root cause analysis*'. While many disturbances take place on a daily basis, the severity, scale and impact can vary widely, and as such they propose to classify disturbances by making a difference between internal-and external disturbances, by level of impact or by the known-ness (new events or known issues). They point to common stages companies adopt when facing disturbance in production: '(1) detection, (2) diagnosis of the immediate cause, (3) mitigation to re-establish normal conditions, (4) root cause analysis, (5) prevention and (6) prediction'. A more comprehensive approach to resilience strategies for industry is provided by the WEF, who introduced a resilience compass[17] displaying key strategic attention points for companies to monitor and act upon, being (1) Simplified product portfolio design, (2) Smart customer orientation, (3) Financial visibility and agility, (4) Diversified customer distribution network, (5) Robust and transparent logistics, (6) Responsive manufacturing set-up (7) Strategic supplier relationships and (8) Advanced planning tools.

[13] Brüning, M., Hartono, N. T. P., & Bendul, J. (2015). Collaborative recovery from supply chain disruptions: characteristics and enablers. *Research in Logistics & Production*, 5.
[14] Parast, M.M. and Subramanian, N. (2021), "An examination of the effect of supply chain disruption risk drivers on organizational performance: evidence from Chinese supply chains", *Supply Chain Management*, Vol. 26 No. 4, pp. 548-562. https://doi.org/10.1108/SCM-07-2020-0313
[15] Ponomarov, S. Y., & Holcomb, M. C. (2009). Understanding the concept of supply chain resilience. The international journal of logistics management, 20(1), 124-143.
[16] Ito, A., Hagström, M., Bokrantz, J., Skoogh, A., Nawcki, M., Gandhi, K., ... & Bärring, M. (2022). Improved root cause analysis supporting resilient production systems. *Journal of Manufacturing Systems*, *64*, 468-478.
[17] See https://www.weforum.org/publications/the-resiliency-compass-navigating-global-value-chain-disruption-in-an-age-of-uncertainty/

From the above lists of resilience capabilities or competences, a strong focus is put on what companies or organisations can do once the external risk has manifested and a disturbance or disruption has-or is taking place. However, there as in increasing need to also improve forecasting- and anticipation and detection competencies as part of a resilience-toolbox. Once a risk has been established, the next step is understanding to what extent and in what timeframe a company can react and come up with a proper response. Such a response can play out on different levels, ranging from derisking strategies on supply chain level to reconfiguring machines and tools on the shopfloor. From there, ideally lessons are learnt on several levels that contribute to resilience capabilities within a company or sector. The figure below provides an organising principle for the paper, via which we will address the different phases and connected tools, methods ('solutions') that we are developing and testing in the respective projects.



In summary, in this paper we will follow the 'flow' of resilience capability building and we will treat the different steps via examples from two ongoing research-and innovation projects funded under the European HEU program. We will start by briefly introducing the projects and the industry pilot lines within these projects.

How to address resilience in practice – resilience challenges from a variety of EU industries

Addressing resilience in manufacturing through the lens of digitisation

The goal of two projects funded under the HEU program is to increase resilience via digital tools and solutions for manufacturing[18]. Flex4Res focuses on achieving resilient manufacturing by utilizing advanced platform-based techniques. These techniques leverage cutting-edge technologies, including Gaia-X and International Data Spaces (IDS), to enhance data sharing

[18] See https://cordis.europa.eu/programme/id/HORIZON_HORIZON-CL4-2022-TWIN-TRANSITION-01-01/en for call details

across the supply chain. Central to Flex4Res is the integration of resilience assessment and reconfiguration services toolboxes, which provide critical support for identifying vulnerabilities and facilitating dynamic adjustments in manufacturing processes. Additionally, Digital Twins (DT) act as a virtual representation of the manufacturing network, enabling effective planning and testing of reconfiguration processes before implementation. Moreover, DTs are implemented using Asset Administration Shell technology, which allows to connect different sorts of data across different manufacturing assets if they have been made digital (data from machines, planning, materials, logistics etc.). This allows manufacturers to anticipate disruptions and adjust their operations accordingly. In theory, such a holistic approach complements lean management practices, improves information sharing among stakeholders, enhances coordination, and fosters adaptable, resilient manufacturing environments aligned with Industry 4.0.

In the R3group project (which stands for *resilient rapid reconfigurable production process chains*[19]) the core topic is to increase resilience among the industry partners by developing different digital- and cyber-physical tools. These tools should help in anticipating external factors relevant for a specific market, develop strategies that make it possible to adapt and restructure internal company processes, and to make possible rapid reconfiguration of productions cells or larger setups. The project looks at case studies in varying sectors, the common denominator being that all industry partners are European manufacturers of products. Via five pilot lines, a combination of technological solutions or services should help these industrial partners with improving their level of reconfigurability in the face of VUCA events. Following Industry 4.0, we have discerned a set of technological pillars that all need to be involved in order to make a digital thread possible and to allow for digital tools and services for reconfigurability to be deployed. A common platform, based on AAS, will be developed to connect a wide variety of digital tools and services that will provide insights on different levels. On the workstation-level, Digital Twins will enable rapid design space exploration and support optimal decision-making. On the system-level, tools to support rapid reconfiguration will address the logistics of the production line. On the factory-level, decision-support tools will provide for high-level, strategic decision-making, and virtual collaborative environments will be developed to help increase workflows between product designers, material suppliers and planners and machine engineers, while supply chain risk modelling will help in further fine-grain and tailor production capacity.

[19] See https://r3group-project.com/

The pilot line companies

R3group

In the R3group project, there are 5 pilot lines in which reconfiguration is the chosen resilience approach, the project focussing on digital tools and solutions ranging from early warning systems to anticipate on supply chain risks to tool-level digital twins to support rapid reconfiguration.

KF Katty Fashion	Katty Fashion is an SME from Northeast Romania, founded in 2003, with almost 2 decades of expertise in offering bespoke services of collaborative design, product development and excellent garment manufacturing of all categories of women wears for more than 50 EU brands.
Goal	Facilitate sustainable product development and manufacturing through digitalization and reconfiguration
Production Process	KF is already pursuing the transition from the traditional sampling process to the digital sampling process through the integration of collaborative design in a 3D environment
Main challenge	The current challenge of KF is the lack of digitalization and interconnectivity of the production (horizontally and vertically), which limits the degree that the digitalization of the product development workflow can be exploited towards rapid reconfiguration.
Vision	To enable vertical and horizontal integration and capturing valuable data and tacit knowledge generated at the production facilities to support high-level decision-making towards reconfiguration.

GLN	GLN PLAST is a Mid Cap from Portugal, specialized in the mass production of plastic injection parts addressing very different markets such as automotive, consumer goods, medical devices, or food packaging.
Goal	Reconfigurable injection moulding cell for changing demand and material variations
Production Process	Plastic part production via injection moulding. Plastic material is subjected to important fluctuation in price and availability. Moreover, because EU strategy on plastic usage and waste reduction, the use of

	recycled material reference is a new channel to foster in a resilient factory.
Main challenge	The specific challenges are the reconfiguration of the production according to customer demand, by considering the tooling step in order to adapt the CAPEX to the volume and the price of the part. Moreover, another challenge addressed is the reconfiguration of the production regarding material shortage and introduction of a new plastic material reference in the chain.
Vision	The reconfigurable concept is firstly based on the development of a Lego-like evolutive tool for injection molding that enables the plastic parts manufacturer to quickly test a market without purchasing large equipment such as molds. Moreover, by considering the material aspect of the supply chain of manufacturing, the demonstration will integrate the possibility to reconfigure the line according to material-related disruptions, such as quick changes of material references or integration of recycled material.

Gestamp	GESTAMP is an international group dedicated to the design, development and manufacture of metal automotive components.
Goal	Reconfigurable laser-head to adapt to and optimise current production lines.
Production Process	The use case of GES considers design, development and manufacturing of suspension control arms for commercial vehicles. Key manufacturing processes for control arms are cutting, drilling, stamping and welding for local reinforcement.
Main challenge	Even for the same platform from a car manufacturer, individual components can have a variety of references depending on the car model or geographical market. These slight modifications require several changes in the production line, such as modifications of the manufacturing process/strategy, addition of small parts, or new tooling with a detrimental impact on downtime and manufacturing costs. In this context, flexible and reconfigurable production processes become crucial for a cost-effective adaptation of the production, providing the

	functionality and capacity required in the moment it is needed, while avoiding strict dependence to a single component reference.
Vision	Laser technology will be introduced as a solution for reinforcing specific variants of the control arms, avoiding necessity of many tooling to accommodate for different products, and thus enhancing the reconfigurability of the GES production. To identify this optimal configuration DT-based tools will be exploited to facilitate design space exploration. In addition, development and implementation of user interfaces with proper algorithms and protocols for reconfiguration control of the manufacturing process (workpiece setting up routines, process monitoring & control systems, safety chain) will be addressed for a cost-effective reconfiguration

HALCOR Evolving Beyond Copper	HALCOR is the copper and alloys extrusion division of ELVALHALCOR S.A. The current annual production capacity is around 90,000tn of copper tubes and the plant is the largest one in this sector in Europe.
Goal	Material rerouting algorithm to minimize scrap and optimize re-configurability in demand flux
Production Process	Cutting and selection copper tubing for various uses and markets
Main challenge	The key challenges faced by HALCOR is the high product mix in terms of quality requirements and product characteristics. Since QA results and other tube characteristics are not fully transferred horizontally within the production, there is a suboptimal allocation of semi-finished material to final products, limited capabilities for production reconfiguration, increased scrapped rate. In the case of coils, final quality focuses mainly on a number of potential defects per coil, as specified by the customer. Operators at the coiling phase do not have in advance the required knowledge on how many potential defects exist in the coming meters of the tube leading to scrapping several tube meters, when a coil exceeds, or it is estimated that it will exceed the limits set by the customer.
Vision	Halcor wants to eliminate the manual transfer of information horizontally through the factory, as well as vertically to other

	production levels (engineering, management, etc.). This will enable to develop advanced (re)routing and (re)scheduling algorithms to optimize material flow within the production, reduce lead times and costs. These algorithms will merge with the existing Advanced Planning System that is used to assist in production scheduling. The part Digital Twin will enable full traceability and provide awareness to the successive production steps about the quality of the incoming material. Adaptive digital work instructions will be provided to coiling operators and will be constantly updated according to the digital signature of the tube that comes in the coiling station, thus enabling informed decision-making.

gorenje Life Simplified	Gorenje Group is one of the leading European home appliance manufacturers with a history spanning more than 70 years.
Goal	Anticipating and adjusting tool wear to ensure production continuity
Production Process	Stamping of metal parts for kitchen appliances
Main challenge	Household appliances are subject to frequent design changes, since their design is fashion-driven to an extent, related to customer preferences in terms of interior design. Nevertheless, even minor design changes can lead to a significant disturbance of the production line and require several reconfigurations in terms of process and production planning, manufacturing strategies and fabrication of new tooling. A significant bottleneck in the reconfiguration workflow for GOR is the demand for redesign and remanufacturing of tooling (e.g stamping process dies) required during the reconfiguration phase, which can lead to several days of the production line being stopped
Vision	To introduce technologies to support the digitalization and reconfigurability of the production line of GOR, in order to eliminate disruptions in the production flow. Collaborative environments for co-development of the tooling will be introduced, to assess the impact of changes in the design, how it links back to the production and how modifications in design introduce needs for reconfiguration. ROMs (such as springback models) will also be developed, so that design

	changes can be quickly evaluated within the collaborative environment. Integration of supply chain awareness and quantification of supply chain disruptions on the tooling production line will be investigated to calculate sizes such as capacity and lead times and support the scheduling/planning algorithms of the whole production.

Flex4Res

In Flex4Res[20], four industrial use cases have been selected for which the project objectives are pertinent.

Pre-pilot cases

Five pre-pilot cases aim to test and validate the resilience toolbox in different learning factory environments. Initially, various scenarios have been developed to simulate production disruptions and test the effectiveness of the toolbox's mechanisms. These scenarios have been implemented in learning factories equipped with the necessary IT infrastructure. The learning factories have progressively expanded from local to international networks, testing different resilience strategies. Once the toolboxes are tested and fine-tuned, the services will be ready for integration to the industrial use cases. The pre-pilot cases are the following:

- PTW pre-pilot case: Create a generic pre-pilot case, where some of the resilience and reconfiguration services will be validated. This pre-pilot case is the more generic, by taking into account requirements and specifications from all the industrial use cases.
- IFT pre pilot case: Test the essential functionality of the Voestalpine use case. The focus is on data flow, processing, and rescheduling of manufacturing orders based on the shopfloor conditions.
- LMS pre-pilot case: Set up the resilience assessment and reconfiguration strategy services of the Sidenor use case as well as set up the data space connectors and components. The goal is to early validate the performance of the services and receive feedback from the industrial experts.
- IDEKO pre-pilot case: Test tools of the Goimek use case at micro level, focused on: (1) Diagnosis cycles, (2) AAS Management, (3) Data spaces. Moreover, the pre-pilot is set up at the Digital Grinding Innovation Hub (Ideko's facilities), where a Soraluce FMT milling machine has been selected for the testing.

[20] See https://flex4res.eu/

- USI pre-pilot case: Development and testing of tools for the Hans Berg use-case. Focus on sensor integration inside machine tool supporting operational resilience, designing mechanism to measure machine resilience, developing and testing of reconfiguration tools at resource level. Based on the resilience score, the goal is to trigger reconfiguration, early detection of reconfigurations needs and support machine operators to perform reconfiguration tasks effectively.

BERG Forming Technologies	Hans Berg GmbH & Co. KG produces deep-drawn parts and metallic tubular components for the heating and automotive industry.
Goal	Reconfiguration measures after a tool change
Production Process	Adjustment measures are necessary when a tool or material has changed. Currently, it is performed manually, its duration and success depend on the experience of the employee executing it. Due to manual operation and several trials in adjustment, a high amount of material is turned into scrap
Main challenge	The adjustment measures are derived according to the defect pattern due to the absence of necessary information from inside the tool. The knowledge generated by an expert in reconfiguration and tool adjustment is tied to one product and can only be transferred to other products to a limited extent.
Vision	Integration of sensors inside machine tools enhance operational resilience by enabling real-time monitoring and data-driven decision making. The resilience assessment toolbox incorporating resilience measurement module measures machine resilience using historical and real-time data, and triggers reconfiguration as the resilience score descend. Reconfiguration toolbox comprises of fault detection and human assistance system. Human motion capture technology is employed that helps to identify and maintain knowledge database for corrective actions necessary for reconfiguration. By leveraging artificial intelligence, faults are detected early, and a decision support system suggests reconfiguration strategies accordingly. Operators are guided through human assistance system to ensure effective and accurate machine adjustments. Both the tools are offered as Software as a

	Service (SaaS) on Gaia-X compliant dataspaces. This will reduce the amount of produced defective components, the time required to reconfigure the tooling and the need for the experience required to perform the adjustment tasks.

SIDENOR	Sidenor Group produces a variety of steel products (e.g., merchant bars, plates, wide rods and more)
Goal	Constant reconfiguration of supply plans
Production Process	Production processes range from scrap purchasing and metal processing to packaging and delivering to customers.
Main challenge	External and internal disruptions require reallocating the production to different production sites than originally planned. Currently, reconfiguration takes place manually and is based on expert knowledge and spreadsheet calculations. Moreover, decisions taken at the network level are not connected to the reconfiguration needed at the factory level
Vision	Based on a secure data exchange using IDS & Gaia-X connectors and the Asset Administration Shell (AAS) concept, the resilience assessment toolbox will guide the user through the steps for network reconfiguration by highlighting the differences with the current configuration status. In the production scheduler optimisation tool, an Artificial Intelligence (AI) agent will compute the scheduling of Thessaloniki's plant based on the output of the Master Production Scheduling optimisation tool. The resulting schedule will be displayed to the user through a graphical user interface (GUI).

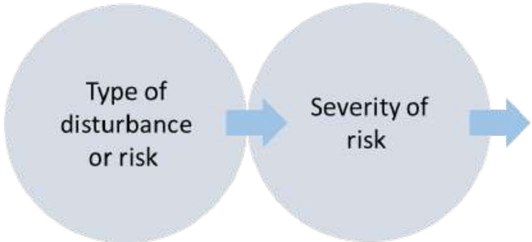
GOIMEK	GOIMEK is specialised in precision and large machining.
Goal	Production planning optimisation
Production Process	Their service begins with the preparation and treatment of high-performance materials, followed by advanced CNC machining including 5-axis milling and grinding, and concludes with strict quality control and final assembly to ensure precision and reliability.

Main challenge	All operations are performed in several working centres. The process steps are flexible but need to be fixed according to the daily production needs. Based on data from the ERP system a master production plan is generated, which is manually turned into a final production plan. Combined with a lack of flexibility these manual tasks cause inefficiencies reducing competitiveness as well as low predictability of production.
Vision	The production planner utilises real-time data from various sources to optimise the scheduling at the plant level proposing reconfiguration strategies and alternate schedules if deadlines are at risk. In addition, the predictive maintenance module will identify anomalies that could lead to failure. Since this will also impact production planning, actions will be suggested to enable a fast reconfiguration of the production to avoid unexpected problems. Moreover, secure data exchange based on the Gaia-X concept will be deployed to facilitate the communication between client and provider, using digital twins and the Asset Administration Shell (AAS).

voestalpine ONE STEP AHEAD	Voestalpine group is a globally leading steel and technology group involved in the production and processing of high-performance materials
Goal	Reconfiguration of manufacturing processes during production
Production Process	Primary forming and alteration of material properties
Main challenge	The products required by customers vary in size and shape and can only be machined on machinery providing the necessary capabilities, which also vary on other factors such as tools. Therefore, highly flexible production planning and scheduling, also depending on the current machine state and manufacturing utilities, is needed.
Vision	A new shopfloor modelling approach will facilitate the integration of ERP- and machine capability as well as current configuration status data into a product, process, and resource model. Based on this a reconfiguration mechanism will be adopted, which allows a flexible flow of products through the factory. Errors will be detected through

	sensors and assessed through case-based reasoning. If necessary, measures for reconfiguration will be suggested. For disruptions coming from the supply chain, the resilience toolbox will allow the evaluation of missing capabilities and the need for reconfiguration. The resulting flexible and agile matrix production will enable the reconfiguration of the manufacturing process during production.

Identifying and mapping risks and disturbances in various industries



If we look at the first steps in increasing resilience capability, we start by the need to understand the type of disturbance or risk that a company or sector is facing, and the severity of that risk to a disturbance or actual disturbance taking place. The need for industries is clear as a recent (2021) WEF report states that, using a resilience self-assessment methods, according to this method only 12 percent of companies can be called resilient. Based on 2 recent HEU funded projects dealing with improving resilience among EU manufacturing industries, and drawing from literature, we discern various levels on which resilience can be improved in practice. Companies can take measures on supply chain level, on factory-level or on resource- or device level.

When looking into several pilot lines developed in the two projects introduced above, based on interviews and company-as well as sector-wide indicators, we tried to find out what are key disturbances and risks identified by these companies that could serve as a trigger to start a resilience-strategy, such as reconfiguring a production line. In the examples below, we provide first evidence from different industries that are trying to increase resilience. In pathways towards increased resilience for EU industries, there are several steps to be taken, from gathering and understanding different types of risks of disturbances per sector or economic activity, understanding the level, and thereby the role of digitisation in resilience strategies, and establishing a baseline of reconfigurability, one of the resilience strategies we are focussing on, as well as applying useful metrics on progress both on reconfigurability and on resilience. The two projects are applying a slightly different scope when it comes looking at resilience strategies and tools to capture disturbances and mitigate risks: the Flex4Res projects takes the perspective of macro, meso, and micro, where *macro* refers to the supply chain, *meso* referring to the production system level and *micro* refers to machinery or device level, whereas the R3group project looks at the factory level, systems-level and workstation level. In both projects, these classifications are used to describe the target area of a project solution or outcome. The common point is that both projects aim to connect levels of disturbances or risks to a variety of possible technical responses (this can be a tool, a method, a computer program) that we propose and are currently developing in our respective projects[21]. Looking into several industry examples via different steps, we start by the types of disturbances and risks[22] described above, and look at different risk categories, divide them into a scale, and where possible a likelihood and severity (linked to the JRCs disturbance indicators of *severity* and *duration* of *exposure*). These scores are based on interviews with the company in question, and desk research on the typical risks or disturbances for the sector in which the company is active. In our examples below, we have differently sized companies active in different domains.

In both projects, some forms of scales have been used in interviews and surveys with the pilots to indicate risks or disturbances, the likelihood of them occurring and the severity if such a risk or disturbance would occur. We provide the scales below:

[21] Another division used in literature is Workstation/Machine level: It is the lowest structuring one, containing single operators and machines that generally perform a technological operation. System level: The proposed-by-literature system and cell levels have been merged into this one. The system level herein considered contains interlinked subsystems made of groups of workstations and material handling used for manufacturing variants of a part or a product family. System configurations can be either cells, lines or production departments. Generally, it is possible to distinguish between production and assembly systems, depending on the activities performed. Factory/Plant level: The proposed-by-literature factory and segment levels have been merged into this one. The factory level herein considered is a production site made of production and/or assembly systems, which can be described as a node of a production network or a supply chain. Network level: This is the highest structuring level. It can be seen as the set of production sites linked by material and information flows along the supply chain.

[22] Throughout the different sources consulted, the terms disruptions, disturbances and risks are used rather loosely. In this paper we see disruptions as stronger, external factors compared to disturbances. Risks and risk classification is linked to these terms but has its own set of definitions – a risk is the product of a likelihood of something to happen times the severity of that happening. While disruptions and disturbances can be seen as different qualitative 'labels' of risks, both terms also refer to the concept of uncertainty, which preceded risks (in order to establish a risk, something must be known about the likelihood and the potential impact or severity, while situations and decision-making under uncertainty means either likelihood or impact or both, are unknown.

Table 1: Likelihood scale

Likelihood [1-5]	Title	Description
1	Rare	Highly improbable
2	Unlikely	Unlikely to occur but possible under certain circumstances
3	Possible	Could occur at some point but not frequent
4	Likely	Occurs more often than not
5	Almost certain	Highly likely; occurs regularly

Table 2: Severity scale

Severity [1-5]	Title	Description
1	Insignificant	No significant consequences
2	Minor	Some inconvenience but no serious damage
3	Moderate	Disruption or damage manageable with effort
4	Severe	Significant damage or disruption that needs immediate intervention
5	Catastrophic	Complete failure or critical damage with long-term consequences

Table 3: Risk scale

Risk [1-5]	Title	Description
1	Negligible	Insignificant risk; minimal impact on objectives
2	Low	Minor risk; unlikely to affect objectives significantly
3	Moderate	Manageable impact but needs attention
4	High	Could cause considerable impact if not mitigated
5	Critical	Severe impact on objectives and requires immediate action

Table 4: R3GROUP & Flex4Res disruption likelihood

Pilot line company	Hierarchical level	Disruption	Level	Likelihood	Severity
Sidenor	Macro	Raw material fluctuation	Critical	4	5
		Changes to the energy cost	High	4	4
		Changes to transportation costs	Moderate	4	2
	Meso	New orders arrival	Moderate	3	4
	Meso	Resources breakdown	High	4	4
	Meso	Raw material issues (unavailability, quality)	Moderate	3	4
Voestalpine	Meso	Task (or job) failure	High	3	3
Goimek, Voestalpine	Meso	Anomalies in machining process	High	3	4
PTW pre pilot case	Meso	Equipment (or labor) failure	High	3	4
Hans Berg	Micro	Components failure	High	4	5
		Maintenance	Moderate	3	3
Katty Fashion	Micro	Operator unavailability	Extremely high	4	4
	Macro	Volatile demand	High	3	4
	Macro	Market changes	Medium	4	2
GLN plast	Meso	Batch size or order quantity policy	High	4	3
	Macro	Sudden hike in costs	High	4	3
Gestamp	Macro	Volatility in automobile part demand due to geopolitical instability	High	5	4
	Meso	Rising energy costs for laser welding	High	4	3

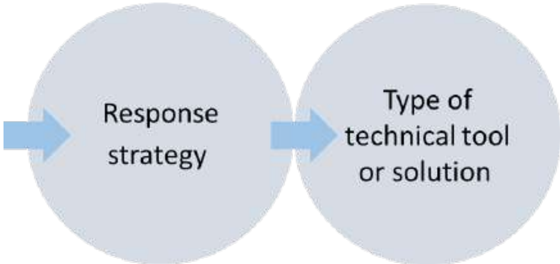
Halcor	Macro	Volatility in copper markets and supply	High	3	4
	Meso/Micro	Loss of material due to suboptimal use of production line and quality control	High	4	3
Gorenje	Micro	Sudden stamping tool breakdown	High	3	5

From the table above we can see that all the companies in the two projects display a variety of risks or disturbances that range from macrolevel (production network) to microlevel (machine or device level). Some of the disturbances mentioned have to do with external factors that can have an impact beyond one company production line such as rising energy costs or geopolitical instability and market disruptions, whereas others are due to internal, productionline factors. Here we can see examples of workforce, skills and the lifetime of machines or tools at types as disruption-factors. In both projects, the abovementioned disturbances can roughly be categorised in sector-wide and often intra-national disruptions in the supply chain and/or global prices of either raw materials or energy, and in disturbances that take place on the level of the factory, and challenges of keeping production levels stable in a context of volatile demands or of factory-asset breakdown as well as scheduling problems. While the former is at the heart of the topic of resilience, the latter can be equally seen as a resilience challenge, specifically in the context of European manufacturing where it is of key interest to prolong the life of tooling and machinery and where the workforce in manufacturing is ageing.

In discussions with different pilot lines, and the reasons they are participating in research-and innovation projects like these ones, many mention, most logically, the covid-19 pandemic and the geopolitical turmoil as core external disturbances for production, with energy prices, supply chains, and changing demands affecting day-to-day operations. Regulations are hardly ever mentioned as a source of disruption, or at least not in the short term. One of the recurring themes among many of these companies is information sharing, planning and accessibility. Digitisation of SMEs, as it turns out, has not gone as far as perhaps hoped, with digital integration on a company level being only at early stages in many of our pilot line examples. A striking yet perhaps obvious point is that many departments within SMEs still work in digital silos, with elements such as company strategy, goals, planning or budgets often not clearly communicated or accessible. Also, a myriad of tools and portals for both administrative- and substantive tasks are often used in parallel, with a clear data-as-company-asset strategy or plan missing. Yet, a clear digital strategy and roadmap is a precursor for increasing resiliency-and reconfigurability capacity-building.

In the section below we delve into different anticipation- and response strategies to external disturbances and the technological tools we are developing in the two project that are aimed to increase resiliency among these companies and ideally the wider sector they are a part of.

Tools to address resilience and reconfiguration



Once a risk or disturbance has been identified and marked as significant to such an extent that it can lead to disruptions in production, the next step is to find the right response. This response should fall within the boundaries of what a company is able to do or is in control of, or the levers it is able to pull. The earlier-mentioned resilience capabilities compass, and other frameworks can prove informative in establishing a way for companies to self-assess their level of resilience vis a vis a particular kind of disturbance. Much in line with the Digital Maturity Assessment tool that exists for SMEs[23], there is a need for assistant in resilience-self assessment which can guide companies to develop better strategies and make more targeted investments in shopfloor equipment and personnel training, to name a few.

In both projects we are developing tools that address resilience challenges on different levels (macro, meso, micro) and that all have a digital core or component. In both projects, reconfigurability plays a role as a resilience-strategy or response. We will briefly highlight a couple of such tools on each level and will discuss 3 tools resilience- and reconfigurability tools in detail, one on each level. After this section, we will discuss strategies and challenges for increasing resilience in-and of manufacturing.

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[23] See https://european-digital-innovation-hubs.ec.europa.eu/knowledge-hub/guidance-documents/overview-digital-maturity-assessment-tool-dmat

Table 5: Examples of different tools to increase resilience and reconfigurability capabilities

Resilience	Project	Macro	Meso	Micro	Responds to Core trigger	Sector
	Flex4Res	Resilience assessment – Supply chain			Changes to the raw material prices, changes to the transportation costs	Metal sector
	Flex4Res		Resilience assessment –Shopfloor value stream		Equipment (or labor) failure	Metal sector
	Flex4Res			Resilience assessment –Resource	Resource breakdown	Metal sector
	R3Group	Supply chain risk modelling			Before a trigger – the tool is the basis for reconfigurability triggers	Several (metal, textile, plastics, copper)
	R3Group		Weak signals analysis		Before a trigger – the tool is the basis for reconfigurability triggers	Several (metal, textile, plastics, alu welding)
Reconfigurability	**Project**	**Macro**	**Meso**	**Micro**	**Responds to Core trigger**	**Sector**
	Flex4Res	Master Production Scheduler			Planner trigger tool to compute new plan	Metal sector
	Flex4Res		Productions scheduling tool		Planner trigger tool to compute new plan	Metal sector
	Flex4Res			Fault detection and human assistance system	Trigger and support worker to perform reconfiguration	Metal sector

	R3Group		Virtual Collaborative Environment for quick redesign		Triggered by design and planning/production outlook	Textile sector, plastics sector
	R3Group		Productions scheduling tool to minimise scrap		Triggered by production planner	Copper tubing sector
	R3Group			Automatic mold insert replacement to adapt to new demand or material change	Triggered by task programmer/operator	Injection moulding sector

Deep dive macro tool (Flex4Res)

Production process

One pilot line concerns a steel manufacturing group that produces a large variety of steel products, i.e., wire rod coils, rebar coils, straight rebars etc., used on multiple industrial sectors. Specifically, the facilities within the steel manufacturing group include enterprise-level operations, warehouses, and manufacturing plants, all integral components of their steel production infrastructure. Furthermore, the steel manufacturing group spans nine facilities across four countries. The presence of uncertainties and disruptions in the operating environment poses significant risks to the execution of a supply chain plan of 6 or 12 months, potentially leading to deviations from planned schedules, increased costs and compromised fulfilment of customer requirements.

Resilience – and reconfigurability challenge

A Master Production Scheduler (MPS) is a reconfiguration strategy service, aiming to compute a supply chain plan. The tool is dealing with planning the production, storage, and transportation of certain commodities, in a profitable and effective manner for the organization. By forecasting market demand for a decision horizon of one or five years, the MPS aligns production and operation planning with demand fluctuations, helping manufacturers optimize resource allocation and adjust to disruptions. Due to the fact that the forecasting the market demands, raw material prices, energy costs etc. is difficult to be done accurately for a decision horizon of 1 or 5 years, there is a need to proactively assess how resilient is the manufacturing system and the plan that is selected for the industrial planners. The goal of the resilience assessment service for supply chain is to evaluate the behaviour of the supply chain system under different unexpected circumstances, before the application of a supply plan[24].

Proposed solution

In order to assess the resilience of the supply chain system or plan, the Penalty of Change (PoC) methodology is utilized to estimate how a system will be affected by potential external or internal changes, such as machine malfunctions or market shifts. It calculates the expected cost of these changes by multiplying the penalty (cost) of each scenario by its probability of occurring[25]. This method requires defining scenarios, their probabilities, a predefined objective function, and the penalties. The final result is the sum of all penalties adjusted by the likelihood of each scenario, offering an assessment of the system's resilience. The resilient assessment approach is used to assess different supply chain plans, with same input, but applying different business constrains (i.e., scrap plan, demand, plan, operational models for the facilities etc.), and support the industrial planners to select the most resilience plan that maximize the overall profitability of the production network.

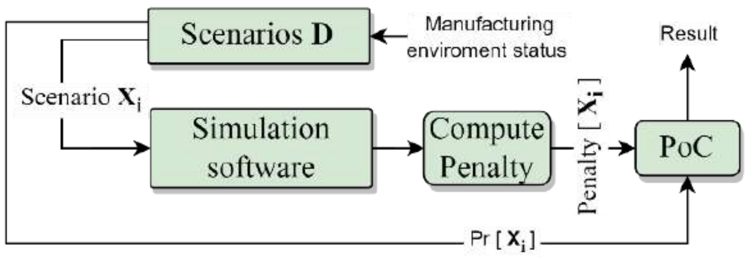


Figure 4: Resilience assessment approach utilizing the Penalty of Change (PoC) methodology: Macro level

[24] Bakopoulos, E., Sipsas, K., Nikolakis, N., & Alexopoulos, K. (2024). A Digital Twin and Data Spaces framework towards Resilient Manufacturing Value Chains. *IFAC-PapersOnLine*, *58*(19), 163-168.
[25] Alexopoulos, Kosmas, Ioannis Anagiannis, Nikolaos Nikolakis, and George Chryssolouris. "A quantitative approach to resilience in manufacturing systems." International Journal of Production Research 60, no. 24 (2022): 7178-7193.

Impact for the company

Based on workshops with industrial experts, the expected benefits of implementing the resilience assessment service for the supply chain aims to improve a) the overall profitability of the network through optimized production processes, b) enhanced resource utilization, and c) reduced operational costs.

Deep dive meso tool (Flex4Res)

Intro company and case/production process

The production process in the steel manufacturing group involves various stages (See deep dive macro tool), from raw material procurement to the final production of steel products. However, disruptions such as unplanned machinery breakdowns, unexpected orders, or raw material shortages can lead to significant production delays and deviations from the planned schedule. These disruptions complicate short to mid-term planning (weekly, daily).

Resilience – and reconfigurability challenge

The primary challenge is the need to quickly adapt to unforeseen disruptions, such as machinery breakdowns or sudden changes in customer orders, which can vary in terms of complexity and urgency. These disruptions can lead to shifts in production priorities, requiring fast reconfiguration of resources and production schedules to minimize downtime and meet customer demands. The ability to maintain continuous production and optimize resource utilization under these conditions is a key challenge. To overcome these challenges, it is essential to integrate advanced resilience mechanisms and adaptive scheduling systems that enable the plant to respond swiftly and efficiently, minimizing the impact of disruptions on overall production performance.

Proposed solution

The proposed solution to address resilience and reconfigurability challenges involves a Production Scheduling tool to compute the production schedule. This tool, through the PoC methodology, will proactively simulate production disruptions and evaluate the impact of reconfiguring production schedules. By leveraging a digital twin implemented with the Asset Administration Shell technology, the tool ensures quick adaptation to unexpected events such as new orders or machinery breakdowns. It enables dynamic re-scheduling, and effective resource reallocation, maintaining operational continuity and optimizing production efficiency.

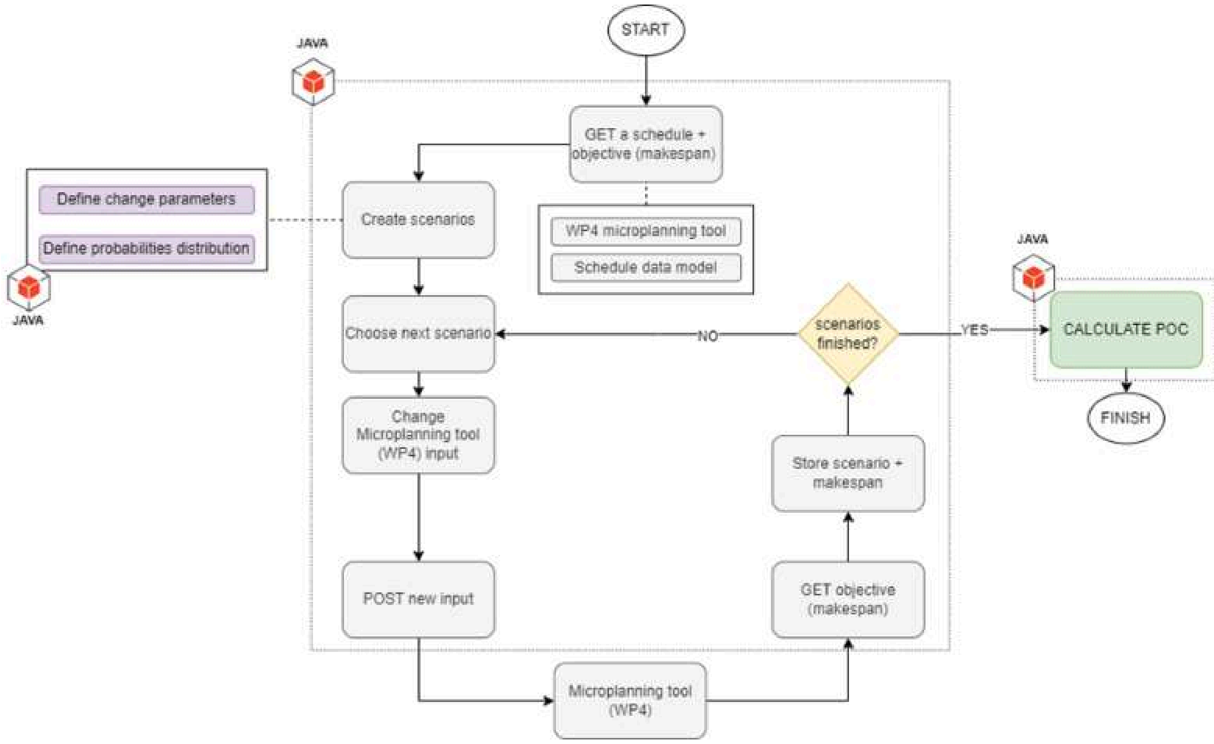


Figure 5: Resilience assessment approach utilizing the Penalty of Change (PoC) methodology: Meso level

Impact for the company: Based on workshops with the industrial experts from plants of the group, the expected benefits of implementing the resilience assessment service for the production system aims to improve a) minimize production downtime, b) enhanced resource utilization, and c) reduced reconfiguration time.

Deep dive meso tool (R3group)

Production process

Focussing on the supply chain aspect of this pilot line, KattyFashion's supply chain includes multi-tier suppliers, with material coming from different parts of Europe (mainly Italy and France). These materials are transported by road or air, depending on customer delivery requirements. Once production is complete, finished garments are distributed to client distribution centres across Europe.

Figure 6: Typical production steps in textile manufacturing

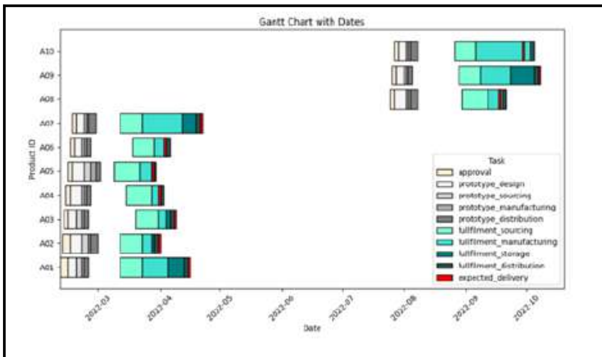
Resilience – and reconfigurability challenge

A company in the sector of textiles and garment manufacturing, KattyFashion is dealing with high supply chain volatility, and disruptions can have major effects on the production line and capacity. They operate in a highly competitive environment influenced by evolving regulations and demand volatility. The company faces limited visibility beyond first-tier suppliers, making risk mitigation strategies crucial. Additionally, KF has no flexibility in supplier selection, as materials must be sourced from suppliers chosen by the client or OEM. This constraint reduces agility in managing supply disruptions. Such disruptions can have a major effect on the end-to-end order lifecycle. The main resilience challenges are, in relation to supply chain risks:

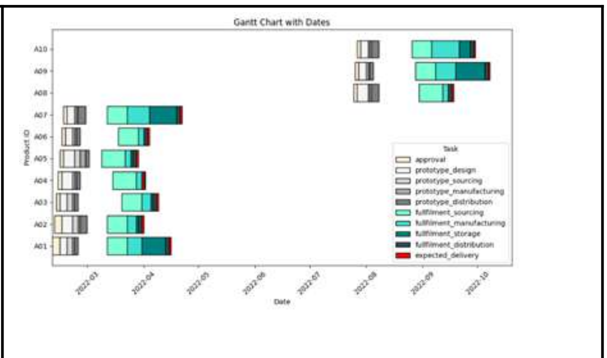
- Market Changes and Demand Volatility – Rapid shifts in consumer preferences and regulatory changes require early detection and proactive adaptation.
- Employee Unavailability – Labour shortages can disrupt production schedules and reduce operational efficiency.

Proposed solution

One of the tools developed for this pilot line is a Supply Chain Digital Twin. In this Digital Twin, the prices-and sources of raw materials are tracked, and both in-company and external data is used to train and test different models in relation to several scenarios (business as usual, do-nothing scenario with demand variation, do-nothing scenario with materials shortages). Moreover, the DT covers different scenarios related to personnel shortages and/or fall out and the costs of finding and retraining or upskilling current-or new personnel. Below an impression of some of the first SCDT results, showing the impact of change in demand on resource scheduling:



Orders scheduler (Demand +30%)



Orders scheduler (Demand -30%)

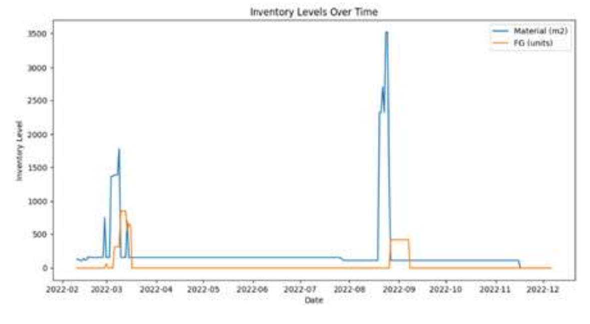
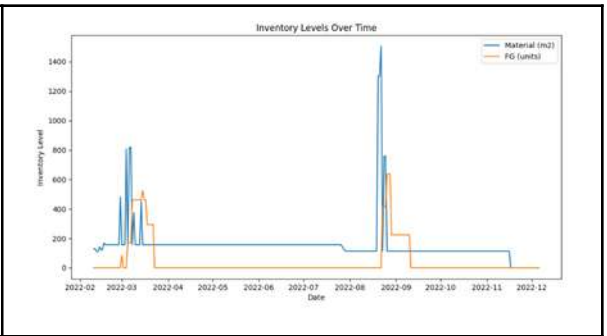
	
Inventory pipeline (Demand +30%)	Inventory pipeline (Demand -30%)

Figure 7: DT prediction for different disruption scenarios for textiles

Impact for the company

As for the material- and demand DT, we can see that a 30% demand increase compresses production schedules, creating potential bottlenecks, while inventory levels spike due to frequent replenishments. In contrast, a 30% demand drop leads to more relaxed scheduling, reducing operational strain but increasing resource underutilization. Inventory remains stable, minimizing supply chain pressure but risking inefficiencies. The Gantt chart reflects extended cycle times, allowing more flexibility. By integrating optimization models, the company can enhance both resilience and reconfigurability, dynamically adjusting operations to maintain efficiency and adaptability across varying demand scenario. As for the Personnel DT, the model enhances the company's resilience and reconfigurability by improving its absorptive, flexible, and transformation capacities. Training programs ensure employees can adapt to new machinery; while hiring and managing part-time workers offer and flexible staffing approaches improve adaptability, while labour forecasting supports long-term strategic planning.

Deep dive micro tool (R3group)

Production process

In the case of GLN Plast, the production process we focus on is that of injection moulding. Serving many different OEMs, GLN produces parts that are complex in geometry and high in volume. Both the chosen material and the quality level sought after are set by the external client.

Resilience – and reconfigurability challenge

For GLN, the challenges related to resilience are connected to the ability to adapt to market demand changes, which are slight changes or adjustments needed for a product, as well as fluctuations in material availability and quality due to geopolitical developments and regulation in relation to the update of recycled material in their production lines. In terms of reconfigurability, one of the challenges with injection moulding is the time and costs of mould development and the relatively low level of digitisation of injection moulding machines to other parts of the production process, such as quality inspection. While the injection moulding process is extremely effective for the mass production of low-cost, high-quality plastic products, the mould itself is a significant bottleneck to reconfigurability. Even the slightest design change of the final product requires the redesign and remanufacturing of the mould cavity, leading to significant capital expenditure and lack of reactivity to market demand.

Proposed solution

To facilitate the reconfigurability of plastic forming processes, we have developed an approach for modular moulds for rapid reconfigurability, thanks to interchangeable mould inserts, standardized interfaces for insert clamping and cooling that enable fast mould cavity exchanging. While interchangeable mould inserts already exist commercially, the solution developed here is aimed at being able to connect all the steps in the process digitally, from material characterisation to quality prediction, process monitoring and quality control, and to automate as many steps as possible in the reconfiguration process. Below an image showing the virtual setup of the reconfigurable injection moulding cell, and the digital thread architecture of the cell.

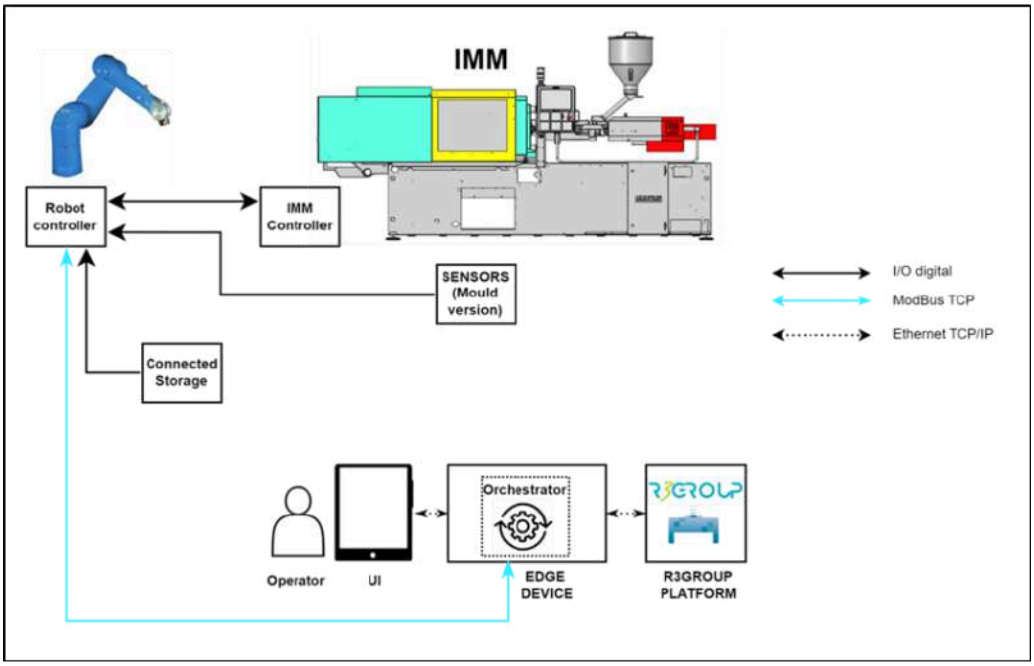


Figure 8: simplified schedule of injection machine automation for reconfiguration

Impact for the company

As for the product chosen for the pilot, among the 285 commercial references produced by GLNP, 4 parts of interest for R3GROUP have been selected. All these proposed parts are available in several versions. Below the design of the different changeable in-mould inserts and the tested mould with the 2 product variants. The product has 2 versions, A and B, that can be produced with the reconfigurable injection moulding cell by changing inserts in the mould.

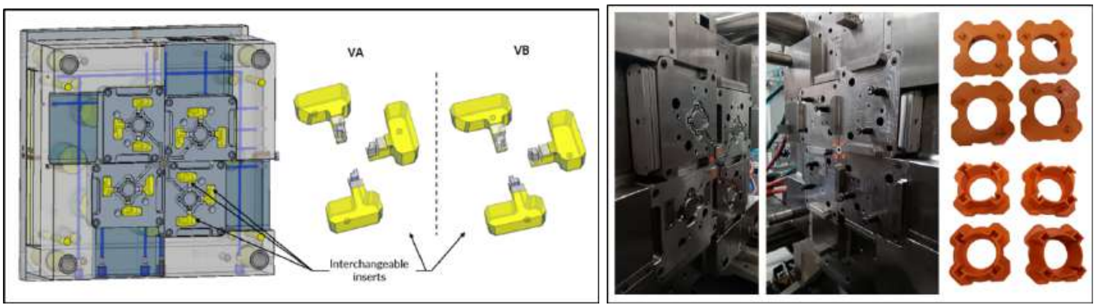


Figure 9: different mould inserts ensure quick versioning of products within the same product family

To evaluate the relevance of the solution adopted by GLNP, a comparison with conventional solutions has been made by looking at the initial market condition followed by market changes. For each situation, the impacts on CapEx, on process cost per part, on production reconfiguration time, and on reactivity to market evolution (tool manufacturing lead-time) have been calculated. By comparing three different manufacturing solutions for the challenge of dealing with different versions[26] of a product with different market scenarios, an economic assessment was done on the viability of our reconfigurability solution. In 3 following scenarios, we have looked at the consequences for the capex of our solution, being

- a major change in the market occurs, and the need of version A drops to 25% while the need of version B increases to 75%,
- introduction of an additional version C, which is a combination of version A and version B. The new volume mix is now established at 25% of A, 25% of B and 50% of C
- the regulation applicable to this product is modified in some countries, leading to the introduction of an additional version D. The new volume ratio is set to 20% of A, 20% of B, 20% of C and 40% of D.

In this example, we can see that rapid reconfigurability, while perhaps needing initial higher capex, over time could become attractive both in terms of costs and time needed to adjust to production line to new demands.

Resilience and reconfigurability strategies

Resilience in manufacturing and supply chain systems is critical for ensuring that operations can withstand disruptions and maintain continuity. Resilience can be increased in two ways: 1) by making plans (such as sales and operations plans, production plan, production schedule) more robust or 2) by enhancing the environment's ability to respond to and recover from disruptions. These approaches can be categorized into proactive and reactive strategies, each contributing to a more resilient system.

Making resilience plans more robust

Building a robust resilience plan for manufacturing involves both proactive and reactive strategies that work together to ensure systems withstand and recover from disruptions effectively. Proactively, resilience is built by identifying potential risks, such as supply chain disruptions or machinery failures, and preparing for them. Predictive analytics powered by AI can anticipate problems like equipment breakdowns, enabling preventive maintenance or adjustments to production schedules. Additionally, integrating flexibility into planning, such as diversifying suppliers and having adaptable production strategies, ensures systems can quickly adjust to changes in demand or resources. Reactive strategies are equally important, where they focus on how quickly and effectively a system can respond when unforeseen disruptions occur. Tools like dynamic scheduling, which adjusts production plans in real-time, help minimize downtime in response to issues like machine failures or material shortages. Having contingency plans and backup resources in place further ensures that production can resume quickly after a disruption. A robust resilience plan combines both proactive measures, such as forecasting and flexibility, and reactive tools, like real-time adjustments and recovery plans, creating a manufacturing environment that can not only withstand but also recover swiftly from disruptions.

Making the manufacturing environment more resilient

Making the manufacturing environment more resilient involves creating a flexible, adaptive system that can respond effectively to both anticipated and unexpected disruptions at different hierarchical levels i.e., macro (supply chain), meso (factory operations), and micro (devices and machines). While planning-level robustness is essential, true operational resilience is achieved when the physical and digital layers of manufacturing are designed to quickly adapt. For supply chain level disruptions, such as delayed deliveries, material shortages, or market volatility, manufacturing environments can increase resilience by implementing systems that decouple local production from external dependencies. For example, Katty Fashion has integrated a supply chain digital twin that simulates material delivery delays and workforce fluctuations, allowing factory managers to reschedule batches, redistribute labour, or substitute processes in anticipation of external disruptions. Similarly, Sidenor's advanced planning tools integrate market signals and raw material pricing data directly into shopfloor scheduling logic, enabling proactive reallocation of production resources across multiple facilities.

This transformation relies on embedding reconfigurability directly into the production environment, enabling systems not only to follow updated plans but to autonomously respond to disruptions. For example, GLN Plast has developed a modular injection moulding system that allows for rapid swapping of mould inserts, drastically reducing the lead time needed to shift between product variants and improving responsiveness to material changes or market volatility. At the system level, this form of embedded resilience requires the integration of advanced decision-support tools with production hardware. In Halcor's copper tube production, material routing algorithms and part-specific digital twins allow semi-finished materials to be dynamically reallocated based on real-time quality assessments. This not only reduces scrap but supports continuity under fluctuating supply or specification demands. One of the most effective ways to operationalise resilience is to reduce the dependency on human-only reconfiguration decisions. At Hans Berg, for instance, a human-assistance system tracks expert tool adjustment patterns and builds a digital knowledge base to guide less experienced workers through disruption events. This ensures knowledge continuity, a critical but often overlooked component of environmental resilience.

Environmental resilience also depends on the vertical and horizontal integration of information systems, linking machine-level data with planning tools and sector-wide indicators. While federated data spaces and asset administration shells enable this technically, the key is aligning workflows so that operators, engineers, and planners respond to the same disruption cues. In Gorenje's stamping line, for example, ROM-based simulations help assess how design tweaks impact tooling lead times, supporting better design-to-manufacturing alignment during reconfiguration. A resilient manufacturing environment is not simply more automated, but it is more aware. This includes real-time feedback loops, anomaly detection models tied to reconfigurable responses, and distributed control mechanisms. The goal is not just to recover from disturbances, but to continuously adapt with minimal coordination friction. Crucially, embedding resilience into the environment supports not only faster recovery but long-term competitiveness. It enables companies to maintain quality and delivery precision despite volatility in labour availability, raw material access, or market demand, all of which were highlighted by pilot partners as recurring challenges.

Discussion – the role of digital tools in increasing resilience

Awareness

Raising awareness among industries about digital tools for resilience requires demonstrating their tangible benefits in minimizing disruptions, optimizing resource utilization, and ensuring operational continuity. Showcasing real-world case studies where digital twins, AI-driven services, and federated data spaces have improved adaptability can build trust in these technologies. Engaging stakeholders through hands-on workshops, pilot programs, and interactive demonstrations will allow companies to experience how digital solutions enhance decision-making and flexibility. Additionally, providing clear roadmaps for gradual adoption, starting with small-scale implementations before full integration, can help industries navigate the transition with confidence, ensuring long-term resilience in an increasingly complex manufacturing landscape.

Anticipation

Anticipation in industrial resilience involves proactively identifying potential disruptions before they occur and implementing strategies to mitigate their impact. By leveraging predictive analytics, AI-driven forecasting services, and digital twin simulations, industries can enhance their ability to foresee supply chain bottlenecks, equipment failures, or shifts in market demand. This forward-looking approach allows companies to develop contingency plans, optimize resource allocation, and ensure continuity even in uncertain conditions. Industries benefit from anticipation by reducing downtime, minimizing financial losses, and improving overall efficiency. Predictive maintenance can prevent unexpected equipment failures, while scenario simulations help assess the impact of different disruption scenarios on production and supply chains. Additionally, integrating real-time monitoring systems enables businesses to detect early warning signs and respond swiftly. To maximize these benefits, industries must establish data-driven decision-making frameworks and foster a culture of resilience, ensuring they are prepared to act rather than react when disruptions arise.

Adaptation

Industries can enhance resilience by adopting digital technologies such as AI-driven decision support systems, digital twins, and federated data spaces. However, several challenges must be addressed to ensure a successful implementation. Integration complexity remains a major barrier, as many legacy systems are not designed to work seamlessly with modern digital tools. Additionally, data silos within companies and across supply chains limit visibility and coordination, making it difficult to respond effectively to disruptions. High initial investment costs, both in terms of technology and workforce training, can slow down adoption, while employee resistance to new tools can further complicate the transition. Moreover, increased data sharing raises concerns about cybersecurity and regulatory compliance.

To overcome these challenges, industries should implement digital tools incrementally, starting with small-scale pilot projects before scaling up. Standardized data-sharing practices, enabled by federated data spaces, can facilitate seamless integration and improve collaboration across supply chains. Training and upskilling programs are essential to ensure that employees can effectively use new technologies, reducing resistance to change. Cost-effective solutions, such as cloud-based and subscription-based models, can lower financial barriers to adoption. Additionally, cybersecurity must be a core consideration from the outset, with robust frameworks in place to protect industrial data. By addressing these challenges strategically, industries can successfully integrate digital solutions, ensuring greater adaptability to disruptions and long-term resilience.

Conclusions and insights for policy

From the wide variety of resilience challenges across the various sectors displayed above, the two research-and innovation projects, although halfway into completion, we can discern several tendencies that should inform future work aiming to increase resilience in-and or manufacturing in Europe.

Resilience as a new mode of operations

The need to expand the paradigm of ‘just-in-time’ manufacturing with a ‘just-in-case’ resilience response strategy. Although several companies among the use cases presented do have some form of supply chain (risk) monitoring or emergency plans or strategies in place, very few to none have made a connection to either increasing use of digital tools for risk awareness and anticipation or to direct impacts on shop-floor implications, such as reconfigurability. Yet, recent crises and the global geopolitical instability that we are currently facing shows that resilience –capability is not a nice-to-have but a necessity. Long-term resilience planning and forecasting, although very difficult to put into practice in industries that are mostly dealing with short-term planning, can prove lifesaving especially for smaller companies and fragile supply chains. Tools such as resilience self-assessment and supply chain digital twins represent first building blocks in a resiliency-roadmap.

Different levels of measures and tools for reconfigurability and resilience

We presented three different levels on which resilience capability can be improved, and how they are interlinked. Although full integration of these three layers via digital tools is still in very early stages, in the pilot lines presented the goal is exactly that – to develop digital tools for each layer (macro, meso, micro, or sector, factory, production line/machine) and to connect those layers via most likely edge computing platforms. One of the main challenges (and potential gains) identified by almost all companies involved in these projects was the breaking of silos, thus data, between departments and along the value chain. In terms of resilience, improving the information position not only on factory-level but also on value-chain and sector-level is a key factor. However, connecting higher-level supply chain prediction data or demand data to machine-level reconfigurability data is far from an easy task. Even with the help of AI-based tools in programming or data management, deep production process expertise is needed to understand what data is relevant, for whom and when. Much more effort and attention will need to be paid to data and information architecture, digital threads and legacy systems if we want to maximise the added value of digital tools for resilience.

Looking ahead: Short- and long terms challenges

With both project amidst development-and integration at industry sites, we have identified several key insights and challenges related to resilience and reconfigurability for manufacturing:

- Resilience self-assessment tools are necessary to increase awareness about resilience, but uptake is scarce. While some companies in our projects have crisis response strategies, stronger ties need to be made to anticipatory approaches.
- Resilience awareness and strategies can act as an accelerator for data sharing across the value chain (via f.i. data spaces). As supply chain risk signalling tools de facto touch upon multiple actors along the value chain, safe and secure data sharing is key for the further development and improvement of such tools.

- Being able to deal with legacy systems and having a proper data architecture and digital team are key ingredients to ensure useful digitisation on all three layers. We see in all use cases that collecting and using data on machine, cell, or factory level requires knowledge and expertise on legacy ERP and MES systems and a wide variety of data formats and programming languages.
- There are limits to the sphere of influence SMEs and mid-cap companies in manufacturing have on globalised supply chains. Recognizing external risks or disruptions is one thing, being able to act upon them another. More sectorial or regional level intelligence sharing is needed to better anticipate on geopolitical-or other shocks and to formulate adequate responses and support long-term transitions and competitiveness.

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