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Lean Six Sigma towards Industrial Decarbonisation: A Theoretical Framework

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Abstract

The pressing need to reduce carbon emissions compels the exploration of strategies despite technical constraints and cost considerations. This paper investigates the synergies between Lean Six Sigma (LSS) and Industry 4.0 (I4.0) technologies in achieving industrial decarbonisation (ID). Manufacturing practices have undergone significant transformation since the Industrial Revolution, with I4.0 representing a key phase driven by digital advancements. While I4.0 revolutionises production processes, LSS provides practical tools to enhance operational efficiency. Integrating these approaches could be a solution to the urgency of ID. The research aims to bridge the gap between I4.0, LSS, and ID by offering an industry-oriented interpretation of the constraints and capabilities involved. It elaborates on the current topics of the field, underscoring the potential benefits of the integration between the three pillars with a theoretical framework, as well as showing the gaps in the existing assessments. By addressing existing limitations and pinpointing opportunities, the study outlines research avenues and proposes topics for future exploration.

Keywords: *Lean Six Sigma, Industrial Decarbonisation, Industry 4.0, Sustainable Performance*

1. Introduction

The evolution of manufacturing brought an escalation of environmental impacts stemming from irresponsible production practices. In the specific Australian context, the greenhouse gas emissions for 2023 were projected to be approximately 459.7 million metric tons of carbon dioxide equivalent ($CO_{2\text{-eq}}$), reflecting a modest decline of 0.5% relative to the preceding year (-25.4% compared to 2005 levels). The situation is increasingly complex when considering the target of a 43% carbon reduction by 2030 as stipulated by the Paris Agreement (Department of Climate Change, Energy, the Environment and Water, 2024). With this pressing need for industrial Decarbonisation (ID), initiatives towards more efficient use of energy have been pointed at crucial by environmental agencies (Cresko et al., 2022), urging a review of industrial practices to the adoption of optimised strategies.

The pursuit of optimised practices that are both sustainable and efficient has been a constant aim in the current manufacturing context, and as production escalated, Quality Management practices such as Lean Six Sigma (LSS) took place in organisations focusing on reduction of defects by standardizing work procedures (Goyal et al., 2019). Emerging from the Toyota Production System in the 1970s, LSS is an alternative to efficiency increase and waste reduction, becoming one of the main pillars of quality management in several industries (Sim et al., 2022), serving also as an alternative to the ID paradigm.

Additionally, other enablers of this net-zero horizon appear as allies of the LSS methodology. The evolution of industry from the First Industrial Revolution in the 18th Century, with mechanical power with fossil fuels, water and steam (Mourtzis et al., 2022), to a reality with advanced electronic systems and the internet significantly improved the way products are manufactured, incorporating the digital factor into processes, namely Industry 4.0. Its potential impact on how industries source, sort, manufacture and deliver the products and raw materials offers benefits in terms of social and technological impact (Ejsmont et al., 2020) and potentialize LSS towards sustainability.

Even though there is a pressing need to explore alternatives linking LSS to Industry 4.0 for decarbonisation, research has proven insufficient in addressing the topic, often taking general approaches regarding sustainability with no mention of carbon reduction strategies. Additionally, a comprehensive understanding of the theories permeating this main theme is scarce since the existing approaches are not interrelated. This study aims to review the link between the main streams of LSS and Industry 4.0 towards Industrial Decarbonisation and Sustainable Operational Performance. It will do this by listing the main topics around the three pillars (ID, LSS, and Industry 4.0), comprehensively describing the theories, pointing out the gaps of the status quo through a holistic framework, and opening avenues for future endeavours. Section 2 will review the current literature to set the foundations for further discussion. Section 0 will systematically describe the research process for the elaboration of the framework presented in Section 0, containing a thorough review of the topics, leading to the concluding remarks and future avenues in Section 0.

2. Literature Background

Quality Management for Lean Six Sigma

Quality Management (QM) practices encompass several fundamental pillars that are essential for achieving organisational benefits, namely: Total Quality Management (TQM), Continuous Improvement (CI), and Lean Six Sigma (LSS). TQM comprehends a management strategy that streamlines across all departments of an organisation to enhance customer satisfaction, loyalty, and overall quality of products and services, focusing on delivering high-quality service levels (Helmold, 2023). With a similar goal, CI is the general philosophy that all processes and systems can be improved at some level (Benjamin, 2007). However, LSS takes a more practical approach, being the set of consolidated tools utilised in manufacturing industries, further developing into a multiplicity of goals: manufacturing optimisation, defects reduction, process control and productivity increase. Each of the tools deploys a specific activity and helps companies to systematically DMAIC: Define, Measure, Analyse, Improve and Control (Vidal Junior, 2022). Amongst the vast toolset, some specific resources can be highlighted, as seen on Table 6. Thus, with the clear benefits in the direction of resource optimisation (DMAIC), waste reduction (DMAIC), cost efficiency (Just-in-time) and workload balance (takt time), LSS becomes a significant booster of sustainable operational performance in organisations.

Table 6: Tools from Lean Six Sigma

Tool from LSS	Definition	Source
DMAIC (Define, Measure, Analyse, Improve and Control)	A five-step approach applied to improve specific operational areas, focusing on improving productivity and reducing waste.	(Wibowo et al., 2023)
VSM (Value Stream Mapping)	Visually mapping out the flow of information and activities within a system or department to identify opportunities for improvement.	(Lins et al., 2023)
Takt time	Often employed in combination with VSM, represents the demand-driven time at which work should be carried out to achieve a continuous flow of activities and resources, or specifically the operational time required to match customer demand in a number of pieces or units.	(Kozlovská and Klosova, 2022)
Just-in-time	The effort to optimise the supply chain to low inventory levels and consequently low associated costs.	(Dieste et al., 2019)

Industrial Decarbonisation

The paradigm of sustainability management is a must, as deleterious and irreversible impacts such as greenhouse gas (GHG) emissions demand a change in the *status quo* of manufacturing systems (Yin et al., 2023). Thus, as efforts for Industrial Decarbonisation (ID) become more demanding, a better understanding of the scope and strategies around ID is requested since current research is broad and not systematic (Sundaramoorthy et al., 2023). Authors have extensively explored the fundamental elements of the ID challenge, and four pillars were crafted by the USA Department of Energy (DoE) as main strategies: energy efficiency; industrial electrification; low-carbon fuels, feedstocks and energy; and carbon capture, utilisation and storage (Cresko et al., 2022). Regarding energy and electricity, the aid of energy management and efficiency programs and models to support practitioners is urgent in the industrial sector, despite being relatively underexplored (Hasan and Trianni, 2020). Additionally, a greater opportunity emerges when the use of low-carbon fuels and energy sources is an alternative to the reduction of the negative impacts of GHGs. However, the high expenses associated with its synthetic process cast concerns about choosing this alternative over established fossil fuels (McCay and Shafiee, 2020). Carbon capture is often presented as another decarbonisation option, offered in several alternatives, such as membrane separation, adsorption, and cryogenic distillation, each presenting distinct challenges. Nevertheless, the lack of subsidies hinders the adoption by the main manufacturing players (Leonzio and Shah, 2024). In face of those gaps, the adoption of proven sustainable-effective methodologies such as LSS can work as an enabler for organisations to achieve net-zero aspirations (Amjad et al., 2021). Moreover, there is a pressing need to correlate these strategies to the emerging digital manufacturing technologies, which are fertile soil for sustainable implementation (Patyal et al., 2022).

Digital manufacturing and LSS for ID

Digital manufacturing technologies, as part of the Fourth Industrial Revolution, or Industry 4.0, represent a breakthrough in conventional systems by offering the benefits of: a data exchange network with the Internet of Things (Shoikhedbrod, 2023); Artificial Intelligence, simulated environments where machines imitate humans in physical behaviour and decision-making (Kaur, 2023); Cloud Computing, where data storage and processing is made in the cloud (Katsaros et al., 2011); among others. Those advancements could act as catalysers of LSS resources, such as VSM to identify process wastes and DMAIC, leading to an integrated framework that culminates in a green implementation phase where opportunities for improvement of the environmental, economic and social performance of companies may emerge (Amjad et al., 2021). This favourable union of LSS and Industry 4.0 was observed by Kabzhassarova et al. (2021) who analysed the two pillars' separate and joint effects, defining "Lean 4.0" as a positive combo that improves manufacturing efficiency and use of resources. However, scholars fall short when narrowing down the sustainable performance goal to the specific case of decarbonisation. Rana and Jani (2023) proposed a framework for the use of a systematic and optimised approach such as LSS, allied with advanced and digital manufacturing strategies. The observation was able to support decision-makers in the quest for sustainable performance. However, no specific decarbonisation approach is observed when proposing the supportive framework.

The present study will bridge the gap around the topic, proposing a valuable discussion and consolidating the main theories around the streams of LSS, Industry 4.0, Sustainable Operational Performance and Industrial Decarbonisation. Additionally, it will explore opportunities and gaps, indicating avenues to be explored in the future, encompassing all strategies in a visual framework.

3. Methods

The methodological approach adopted four steps: background, review, framework, and analysis. The proposal is unveiled in a structured 11-stage application culminating in the research conclusions. Figure 1 presents the methods applied.

The initial step (A) consisted in a thorough selection of main research streams (Lean Six Sigma, Industry 4.0, Industrial Decarbonisation, and Sustainable Operational Performance). The process was not executed randomly but considered the pressing needs identified by extensive research and based on opportunities found in industrial reports (Trianni et al., 2022).

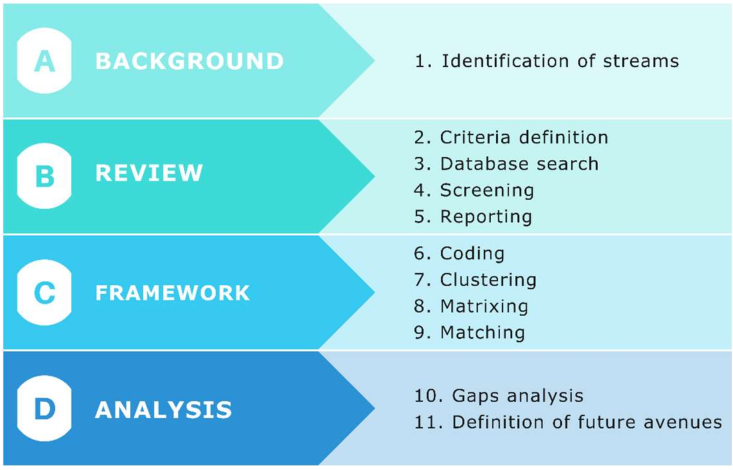
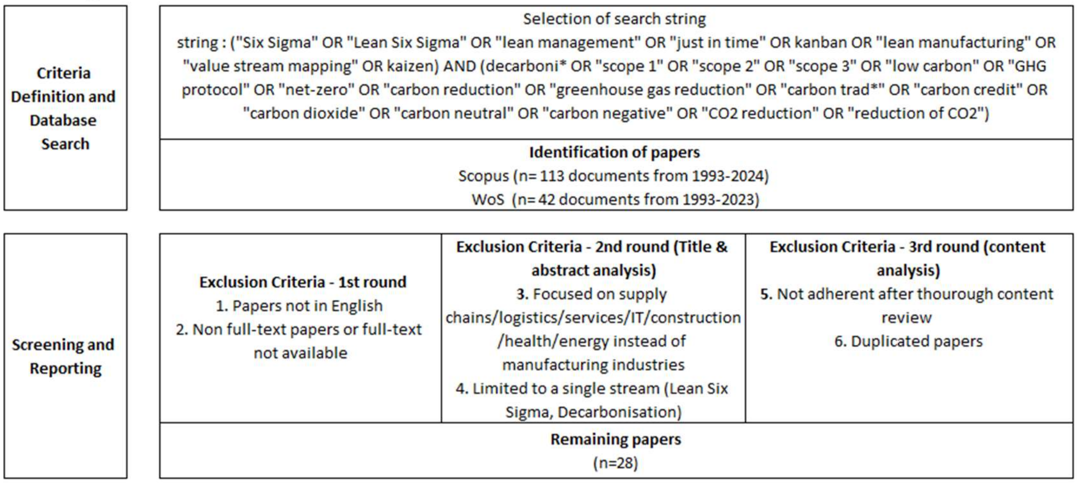


Figure 1: Methodological steps adopted in the research

Step B consisted in four stages that comprised the literature review as a foundational step of the research. This review had as a starting point the research question:

"Under the spotlight of quality management, how Lean Six Sigma practices can contribute to energy efficiency, bringing decarbonisation into manufacturing industries?"

Some criteria were defined for the papers to be assessed, according to key pillars and are described in Figure 2.



Criteria Definition and Database Search

Selection of search string

string : ("Six Sigma" OR "Lean Six Sigma" OR "lean management" OR "just in time" OR kanban OR "lean manufacturing" OR "value stream mapping" OR kaizen) AND (decarboni* OR "scope 1" OR "scope 2" OR "scope 3" OR "low carbon" OR "GHG protocol" OR "net-zero" OR "carbon reduction" OR "greenhouse gas reduction" OR "carbon trad*" OR "carbon credit" OR "carbon dioxide" OR "carbon neutral" OR "carbon negative" OR "CO2 reduction" OR "reduction of CO2")

Identification of papers
Scopus (n= 113 documents from 1993-2024)
WoS (n= 42 documents from 1993-2023)

Screening and Reporting

Exclusion Criteria - 1st round	**Exclusion Criteria - 2nd round (Title & abstract analysis)**	**Exclusion Criteria - 3rd round (content analysis)**
1. Papers not in English 2. Non full-text papers or full-text not available	3. Focused on supply chains/logistics/services/IT/construction /health/energy instead of manufacturing industries 4. Limited to a single stream (Lean Six Sigma, Decarbonisation)	5. Not adherent after thourough content review 6. Duplicated papers

Remaining papers
(n=28)

Figure 2: Step B - Literature Review

The next step (C) was the structuring of the theoretical framework through coding. The method consisted of assigning attributes to the papers according to the content and some categories, inspired by Barratt et al. (2011). A classification table was created to analyse the papers in light of the research streams, focus, gaps, and main theories. Subsequently, the research team created main clusters for similar topics and matrixed the articles in a table view to match the individual topics with common interests from clusters.

After the elaboration and checking of the validity of the framework, the results were analysed (step D) in face of the opportunities for future research and gaps. The analysis consisted of both a quantitative (according to the table quantification where fewer explores streams have a lower number of contributions and, therefore, represent a research gap) and qualitative (according to the content presented in papers) approach to better cover all research opportunities. This evaluation served as a basis for the concluding remarks and direction of future research avenues.

Theoretical framework and discussion

The theoretical framework to be presented in the following section consists of a comprehensive effort to cast light on the *status quo* and opportunities around the decarbonisation strategies using LSS and I40. The foundation principle of the framework creation is inspired by Siva et al. (2016). The selection of topics was not arbitrary but adhered to common theoretical topics found in the explored literature mentioned in the methods section. The topics and fundamental theories were proposed with the intention of characterising any publication across the set of fundamental streams of this research: Lean Six Sigma, Sustainable Performance, Industrial Decarbonisation and Digital Manufacturing Technologies. In line with similar approaches from the existing literature (Sarkis et al., 2011), the perspectives of key industrial decision-makers were considered in the implementation of the theories. Table 7 summarises the framework.

Lean integration towards sustainable benefits with a decarbonisation potential

This topic highlights that the isolated application of Lean Six Sigma (LSS) has limited impact when aiming at sustainable improvement. However, integrating Lean with other resources can yield measurable environmental benefits for manufacturing companies. Data collection was employed following Lean Manufacturing principles for a case study that aimed at reducing production wastes and increasing manufacturing efficiency (Nujoom et al., 2016b). However, the authors affirmed that the quality management methodology, when applied isolated, does not provide a consideration of energy consumption and carbon emissions. According to them, the proper integration of LSS with other computational methods can contribute to sustainable manufacturing systems incorporating several environmental parameters, such as carbon emissions. A thorough review of DMAIC methodology was proposed within the Lean approach (Prashar, 2020), applying the Ishikawa diagram for problem-solving. Applied in a case study for manufacturing in one pharmaceutical industry in India, the approach focused initially on reducing utility costs, and the measurement of CO_2 was calculated based on relation to kWh provided by the equipment. After proper scrutiny, the authors concluded that the integration of environmental sustainability considerations with continuous improvement methods (DMAIC) allows organisations to reduce their ecological impact.

In a different approach, Zhu et al. (2022) did a quick review on Lean & Green systematically provides a methodology for the calculation of carbon emissions. Validating in a case study for a satellite manufacturer, it created a VSM-takt time accounting system and proposes an analysis of improvements with carbon reduction. Additionally, used other consolidated LSS tools as Kanban, 5S and TPM management systems to conclude that single approaches are limited for improving performance; thus, integrating Lean and Green practices is encouraged by internal factors such as risk management, profitability, cost considerations, changes in corporate culture, and a focus on continuous innovation and process improvement. External factors also play a significant role, including customer and environmental pressure, government policies and regulations, and the potential for increased profit by enhancing customer value. Other articles on this topic focused on the need for conventional LSS models to be boosted by proper indicators, however they are not efficient in considering waste and carbon emissions in manufacturing systems (Edtmayr et al., 2016; Nujoom et al., 2019, 2018, 2016a).

Table 7: Theoretical framework for Lean Six Sigma and Digital Manufacturing towards decarbonisation

Topic	**Fundamental theory**	**References**	**Streams (number of papers represented by check marks)**			
			Lean Six Sigma	**Sust. Performance**	**Industrial Decarb.**	**Digital Manuf.**
1. Lean integration towards sustainable benefits with a decarbonisation potential	The isolated use of LSS is limited in the sustainable impact. However, the Integration of Lean to other resources can bring quantifiable environmental benefits to manufacturing companies	(Edtmayr et al., 2016; Nujoom et al., 2019, 2018, 2016b, 2016a; Prashar, 2020; Zhu et al., 2022)	✓✓✓✓ ✓✓✓✓ (all)	✓✓✓✓ ✓✓✓✓ (all)	✓✓✓	✗

2. Mathematical and structural models for decarbonisation with the aid of LSS	Mathematical models can support decision-makers in the accounting of decarbonisation and economic benefits	(Li et al., 2012; Nujoom et al., 2019, 2018, 2016b, 2016a)	✓✓✓✓ ✓ (all)	✓✓✓✓ ✓ (all)	✓✓✓	✗
	Interpretive structural modelling allied with LSS leads to sustainable performance improvements	(Kovilage, 2021)	✓ (all)	✓ (all)	✗	✗
3. Process-oriented approaches of LSS and decarbonisation	The relation between LSS and decarbonisation/sustainable performance optimisation is mediated by each process of the manufacturing system	(Li et al., 2012; Wang et al., 2019)	✓	✓✓ (all)	✓	✗
4. Digital manufacturing as mediator for LSS-sustainability integration	Digital manufacturing technologies act as mediators of LSS towards sustainability	(Kuryło et al., 2023)	✓ (all)	✓ (all)	✗	✓ (all)
5. LSS protagonism	LSS can act as main driver for industrial decarbonisation and sustainable development	(Edtmayr et al., 2016; Kovilage, 2021; Wang et al., 2019; Wu and Low, 2012; Zhu et al., 2022)	✓✓✓	✓✓✓✓ ✓ (all)	✓	✗

Mathematical and structural models for decarbonisation with the aid of LSS

Several authors introduced decarbonisation from a modelling perspective, either working in a mathematical or a structural approach. Firstly, for the mathematical approach, Nujoom et al. (2016b, 2016a) offered a theoretical proposition with validation in a case study for a plastic and woven sacks manufacturer. They have proposed a mathematical model for the measurement of carbon dioxide (CO_2) and energy consumption for manufacturing, where carbon emissions are based on conversion factors depending on energy expenses. In a similar effort, other studies (Nujoom et al., 2019, 2018) concluded that multi-objective mathematical models (based on Lean) incorporating the economic and environmental constraints can support companies in the reduction of total cost, energy consumption and CO_2 emissions for a manufacturing system design. Other approaches deeply apply the VSM method to build the theory that carbon efficiency can be calculated by mathematical models based on LSS tools and Eco-efficiency with the use of conversion factors.

Secondly, interpretive structural modelling (ISM) was utilised in a review of Lean practices (Kovilage, 2021) to create a relationship matrix used to identify Lean (pull flow, lot size reduction, continuous improvement, preventive maintenance, workforce involvement and operational time reduction), Green (water and material reduction, energy efficiency, water pollution prevention and greenhouse gas reduction) and sustainable practices (inventory level management, profit increase, quality management, cost reduction, employee satisfaction, customer service level, lead time, use of resources and waste generation) in companies.

Process-oriented approaches of LSS and decarbonisation

The third topic deals with the dependency between LSS and decarbonisation and the mediating role of each process of the manufacturing system for the final outcome of sustainable optimisation. From the perspective of computer-integrated manufacturing, in the case study of an electronics manufacturer that applied VSM for mapping process parameters, the carbon efficiency could be reflected as the quantification of carbon emissions in the whole manufacturing system. Thus, it is determined by the performance of each individual process within the system. Whenever the efficiency is not adequate, the bottleneck processes are identified as the root cause (Li et al., 2012). On the other hand, Wang et al. (2019) indicated that the only way to achieve sustainable operational performance is by applying quality improvements with a process-oriented perspective, where the individual processes are at the centre of the company's endeavours.

Digital manufacturing as a mediator for LSS-sustainability integration

Kuryło et al. (2023) are the authors who deeply introduced the topic of Industry 4.0 as a mediator for LSS with the aim of decarbonisation of manufacturing industries. In their study, a multi-criteria standardisation of machines in an Industry 4.0 environment has been presented, and the case was applied in a manufacturing environment with the application of TPM and 5S. Solutions with lower energy consumption and overall reduced costs were the effect of the implementation of what the authors referred to as "technological synergy" fostered by standardisation, which aids in eliminating superfluous and often unnecessary warehouse resources. Even though this topic opens an innovative avenue correlating LSS and Digital Manufacturing with a sustainable approach, the attention put into decarbonisation is not extensively covered.

LSS protagonism

According to Kovilage (2021) Lean acts as a protagonist and positively influences Green practices, and afterwards, Green practices affect the sustainable performance measures to an output of reduction in carbon emissions. In this expert-based-interview case study, the understanding of the concepts and theories (mentioned in section 0) of the different but complementary Lean and Green pillars supported Sri Lankan industries in the strive for sustainable improvements. On the other hand, Zhu et al. (2022) highlighted the similarities between Lean and Green, such as waste elimination, environmental efficiency, and increased profits. Additionally, 3R technologies (reduction, reuse and recycling) from Green present the same attributes of Lean production. Furtherly, according to Edtmayr et al. (2016), VSM can be employed as a key tool for the quantification of sustainable benefits (efficient material use for production, efficiency increase and cost reduction), used for carbon accounting and calculation of complex sustainability environmental indicators related to waste and disposals. Other scholars are more cautious to inform that the Just-in-time and Lean workforce had a moderate to major impact on the level of carbon emissions (Wang et al., 2019; Wu and Low, 2012).

4. Conclusion and future perspectives

This study comprised a comprehensive view of the main topics around the streams of LSS, ID, Sustainable Operational Performance and Digital Manufacturing Technologies. The pressing need to address decarbonisation with smart manufacturing allied with LSS was highlighted by the existing literature on the topic. As a valid output, this research presented an extensive framework clustering the main theories and visually indicating gaps in the status quo, both quantitatively and qualitatively.

The quantitative opportunities observed are mostly related to the fact that even though there is a significant amount of Industry 4.0 literature in recent publications, there is a timid number of papers addressing digital manufacturing as an enabler of the pair LSS-decarbonisation, as seen by the number of papers (28) considered in the final framework. This opportunity is graphically seen in the proposed framework by the scarcity of papers that address all streams, mostly when the Digital Manufacturing stream is added. Concurrently, in the qualitative analysis, approaches have taken a generic sustainability discussion, not delving into the current decarbonisation challenge faced by global manufacturing. The observed theories often focus on mathematical models or adopt approaches that put LSS in the centre. However, even though highlighting the decarbonisation aptitude, the approaches do not address the carbon reduction outcome as a tangible result, reflecting it as a goal, or a potential result.

Therefore, opportunities for future studies may reside in the fact that authors have not extensively explored the barriers to the adoption of LSS practices towards decarbonisation. Also, as LSS practices evolved and varied extensively, there is a pressing need for an understanding of those, as much as the contextual factors within organisations that allow those practices to be implemented, namely the LSS capabilities. The relation of LSS capabilities with Industry 4.0 and decarbonisation capabilities will be able to identify possible similarities and overlaps, supporting the elaboration of relationship frameworks for implementation by decision-makers.

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