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CONSTRAINT-MAPPING BASED COLLABORATION PROCEDURE FOR ENHANCING COMMONALITY OF SUPPLIER MANUFACTURING PROCESSES

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Abstract. *It is the most effective way of achieving the low cost without sacrificing quality to exploit the economy of scale of resources. This study suggests a collaborative product-process design procedure for an OEM, who designs a variety of components and outsources their production to a single supplier, and the supplier, who manufactures those components as designed. The supplier needs to maximize commonality of their manufacturing processes to produce them at a low cost, and then the OEM can buy them at a low price. This study defines rules to produce a variety of products with a common manufacturing resource as constraints and proposes an effective negotiation procedure to optimize the tradeoff between commonality and variety by mapping constraints to manufacturing resources and design parameters. It also developed a system to support the procedure by visualizing those constraining relationships. This system and the procedure are illustrated by a case of designing and manufacturing an automotive component.*
Keywords: Commonality, Variety, Constraint, Supplier involvement

1. **Introduction.** For modern manufacturing firms, it is essential to offer a variety of products at a low cost [12]. A firm enables it by sharing a common resource for a variety of products and processes. The degree to which various products share common resources is formally denoted by *commonality* in the literature (e.g., [12]). Although the advantages of commonality have been widely studied [8], it also has the disadvantage of constraining differentiation. A firm needs to optimally balance the tradeoff between commonality with variety. In this sense, Robertson and Ulrich [16] present a general framework to plan common design chunks, which is called a product platform, over a variety of products. A commonality plan and a differentiation plan are negotiated to reach an optimal tradeoff in their framework. Baldwin and Clark [2] propose to define design rules to guarantee independence between physical components and organizations. A manufacturing process can be common while producing a variety of products if they are mutually independent. Sin [19] emphasizes the role of a manufacturing department in a product formulation stage to define design rules and guarantee design-manufacturing independence. Galizia et al. [10] present a decision support system for selecting common components while minimizing the number of unique assemblies and disassembly tasks.

An effort to improve commonality can be expanded to external suppliers as well as internal resources. This study suggests a collaborative product-process design procedure for an original equipment manufacturer (OEM), who designs a variety of components and outsources their production to a single supplier, and the supplier, who manufactures those components as designed. An OEM tries to enhance efficiency by reducing the number of suppliers and increasing purchasing volume from each supplier. The supplier needs to

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maximize the commonality of their manufacturing processes to supply the larger volume at a lower unit price. Since a manufacturing process largely depends on the design of the component, the OEM should consider the supplier's resources when designing their components. Dowlatshahi [7] presents a proposition that early involvement leads to better manufacturability and higher quality. More specifically, an early involved supplier can produce the sourced components in a common flow line [12]. A flow line significantly reduces lead time and cost by eliminating waiting time [17] and mitigating demand fluctuation [18].

It is much harder for an OEM and suppliers to concurrently work together than for the design and manufacturing departments of the same company. They are independent organizations psychologically and spatially departed. The collaboration poses challenges, especially to suppliers. Flankegård et al. [9] state too diverse products and continuously changing requirements make it hard to collaborate with the OEM. According to Adler [1], there are coordination mechanisms by standards, by schedules and plans, by mutual adjustment, and by teams. Persson [15] augments another mechanism of empowering the sourcing department as a moderator between the design department and the supplier.

This study emphasizes the mechanism by standards. Baldwin and Clark [2] also emphasize the necessity of design rules for enhancing manufacturing efficiency. Boer and Boer [4] show, by empirical study, that design-for-variety practices like usage of platforms and standardization are positively correlated with supplier integration. This study physically defines those rules as *constraints* and proposes a procedure to negotiate the constraints. Mapping constraints to manufacturing resources and design parameters (DPs) reveals what constraints optimally balance commonality and variety. It also develops a system that visualizes the mapping relationships to support this procedure.

The existing literature lacks such a procedure or framework, especially at the level of design parameters and manufacturing resources. Most design-related supply chain studies emphasize supply network design problems, as reviewed in Pashaei and Olhager [14]. A recent special-issue collection on 'joint design of products and production systems' [3] also lacks this level of decisions. They consider function-level [11] or process-layout-level decisions [13]. Whereas Dombrowski and Karl [6] state a conceptual framework to integrate a supplier in a product development process as analysis, identification, improvement, and verification, it does not present detailed procedures for implementing each step. In contrast, this study proposes a procedure to collaboratively determine which design parameter values to be fixed or variable and which resources to be shared or dedicated.

The remaining sections are organized as follows. In Section 2, the collaboration procedure for establishing constraints is described. Section 3 presents a case of an automobile manufacturer (OEM) who outsources production of a *rear cross member* (MBR) component to an external supplier to illustrate the suggested procedure. Section 4 concludes the study and presents directions for future research.

2. **Constraint-Based Collaboration Procedure.** This study considers a product family whose members are derivatives of a platform product. The platform is first developed and introduced to the market. Following derivative products differentiate some DPs while carrying over the platform's key functionality, architecture, and layout. Besides, some components may be added or removed for differentiation. All the platform and derivative components are outsourced from a sole supplier. It should be noted that a component indicates an OEM's component whereas it is an end product of a supplier. To avoid confusion, a supplier's subcomponents that compose a component are called parts in this study.

The OEM first provides the supplier with a detailed design of a platform component. The designs of derivative components are fixed later. The supplier installs a manufacturing process to produce the platform. Their final process depends on the design of derivative components. It is the best if the platform manufacturing process can also produce all other derivatives; the supplier can maximize the utilization of resources [5,9]. In the worst case, however, individual derivatives, including a platform, may require independent manufacturing processes. The utilization of each process highly fluctuates depending on the OEM's demand for the corresponding component. This inefficiency also harms profitability of themselves. To maximize the commonality, the OEM and the supplier should collaboratively design components and their manufacturing processes.

This study proposes a procedure, as shown in Figure 1, to support such collaboration. The procedure finally outputs a commonality plan of the supplier's manufacturing process and a set of design rules that the OEM promises to comply with. The supplier guarantees that they can efficiently produce the derivative components designed by these rules. Their efficiency is shared with the OEM. The procedure is divided into three phases: identification, mapping, and negotiation. A decision support system (DSS) is also developed to support the collaboration procedure described above. This system systematically controls relationships between stations and DPs via constraints and visualize them to support negotiation. This system visualizes which DPs are forced to be fixed by a plan to share common stations, and vice versa. Figure 2 shows a screenshot of the DSS.

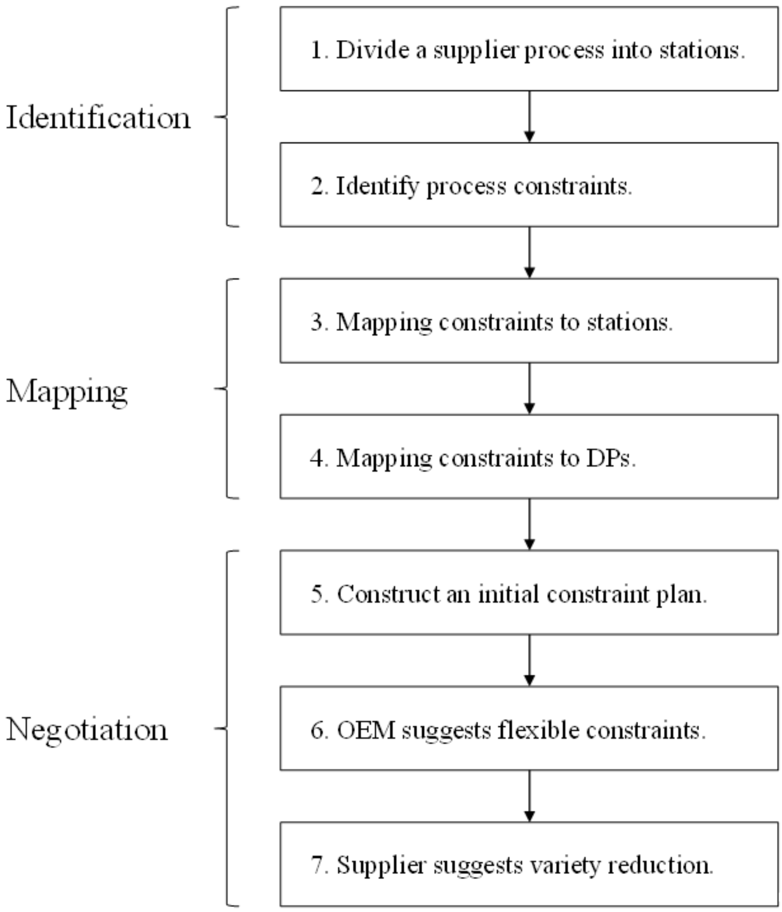


FIGURE 1. A proposed procedure for OEM-supplier collaboration

2.1. **Phase 1: Identification.** The first step of this phase is to divide the whole manufacturing process into station-wise subprocesses. A station is a set of manufacturing resources, such as machines, workers, and tools, conducting one or more consecutive manufacturing operations. In a usual machining process, a station is defined as a workbench and tooling machines. This study defines a station as a minimum unit of sharing manufacturing resources. The manufacturing resources are divided into disjoint stations.

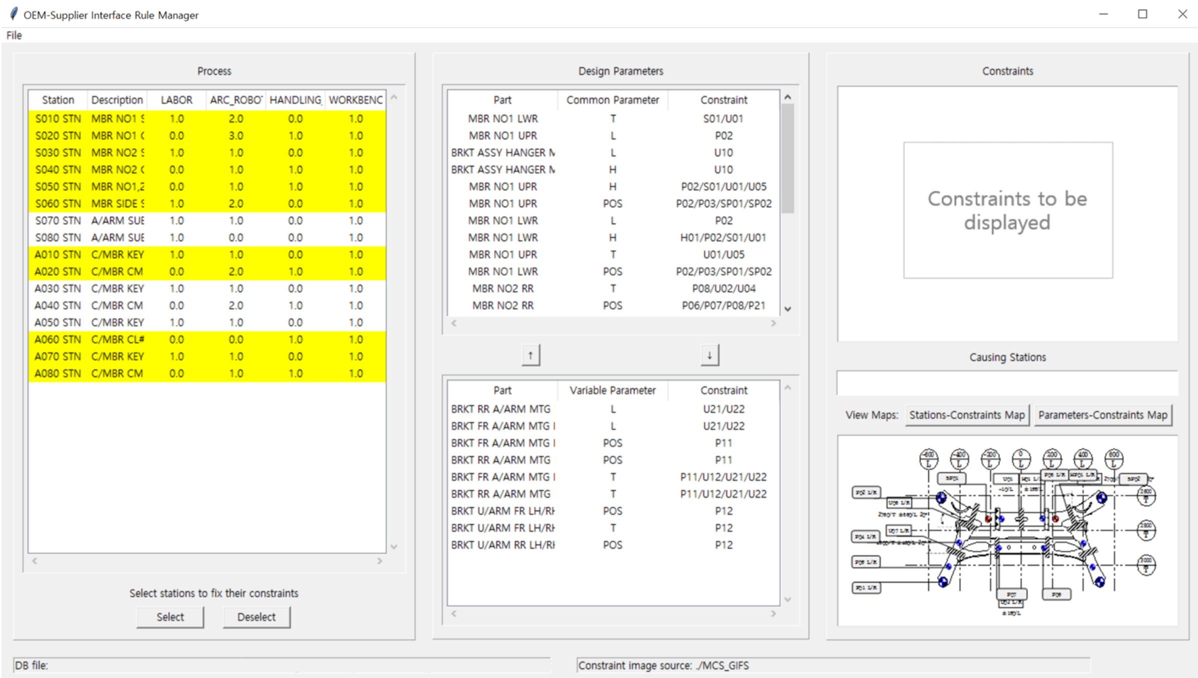


FIGURE 2. A screenshot of the DSS

For instance, if a transfer robot picks a work-in-process (WIP) from one workbench to another, all of them are aggregated into a single station rather than separated into two stations sharing the robot. A station should be defined as small as possible so that one resource belongs to only one station, and a unit operation is not broken down into two stations.

The next step defines manufacturing constraints. A constraint is a process design element that limits producible components in the baseline process. For example, a welding or assembly process uses jigs for holding a WIP on a workbench. If a derivative component is incompatible with the predefined jigs, it cannot be produced by the baseline process. An assembly direction is another example. A process joining a bolt from a left-hand side cannot assemble parts designed to join a bolt from a right-hand side. A constraint is an abstract concept realized in various forms depending on process details.

2.2. **Phase 2: Mapping stations-constraints-DPs.** The predefined constraints are mapped to process stations and DPs in this phase. For notational convenience, let stations be $S = \{i|i = 1, \dots, r\}$, constraints be $C = \{j|j = 1, \dots, p\}$, and DPs be $D = \{k|k = 1, \dots, q\}$. As results of the mapping process, station-constraint mapping matrix SC and DP-constraint mapping matrix DC are obtained.

1) Station-constraint matrix (SC): The matrix SC is an $r \times p$ matrix where $SC_{ij} = 1$, if station i cannot process a component violating constraint j, and $SC_{ij} = 0$, otherwise. Because a station may have several constraints, and several stations share the same constraint, stations and constraints have many-to-many correspondence. For example, jigs usually hold the same location of a WIP during a whole process, and an assembly direction is usually common for a process line.

2) DP-constraint matrix (DC): The matrix DC is a $q \times p$ matrix where $DC_{kj} = 1$, if a change of DP k would violate constraint j, and 0, otherwise. Where a constraint is a jig, a change of the holding section (e.g., width and height) forces the jig to fail to hold a WIP. For an assembly direction constraint, a location and angle of a joining hole should be unchanged.

2.3. **Phase 3: Negotiation.** The negotiation is a process of collaboratively establishing a commonality plan of a supplier and design rules of an OEM. A commonality plan specifies which resources to share between the platform and derivative components. A set of design rules defines which design parameters should be common for all components, and which are free to differentiate. Both a commonality plan and design rules are determined by the constraints that will be sustained for derivative components. This study calls it a *constraint plan*. A constraint plan is represented by a vector $\mathbf{x} = \{x_1, \ldots, x_p\}$ where $x_j = 1$, if constraint j is sustained, and $x_j = 0$, otherwise. The first step of negotiation is to establish an initial constraint plan $\mathbf{x}_0$. An initial plan heuristically selects constraints that commonize as many stations as possible. Let $n(\mathbf{x})$ be the number of stations to share under a constraint plan $\mathbf{x}$. For every subset of C, evaluate $n(\mathbf{x})$ and list them in decreasing order of $n(\mathbf{x})$. The initial plan $\mathbf{x}^0$ is chosen right before $n(\mathbf{x})$ drops steeply.

As the second step, an OEM examines the constraints of the initial plan and which DPs should be common to comply with them. From the DP-constraint matrix DC, k-th DP should be common if $z_k > 0$ where vector $\mathbf{z}$ is $\mathbf{z} = DC \cdot \mathbf{x}$ for constraint plan $\mathbf{x}$. If it an important differentiating attribute of the product, the OEM demands revocation of the related constraints; a set of constraints $\{j|DC_{kj} = 1\}$. Upon the OEM's request, the supplier judges whether to diversify related stations or to make a constraint flexible. A flexible constraint accommodates a certain range of DP values. For example, a tooling pin fixes the location of a WIP with a tooling hole. If tooling hole locations are different between derivative products, the supplier can design a flexible tooling pin that adaptively chooses which hole to bind.

The third step is the supplier's turn. If a high-cost station is dedicated to each derivative component in the initial plan, they request to include more constraints to make it common. Where $\mathbf{y} = SC \cdot \mathbf{x}$ for constraint plan $\mathbf{x}$, station i such that y_i equals $\sum_j SC_{ij}$ can be common between the platform and derivative components. In other words, a station is shared if all related constraints are sustained. If a dedicated station i becomes common, some x_j's should be changed to 1 from 0. Where this modified plan is denoted by $\mathbf{x}^1$, the OEM examines DPs k such that $z_k^1 > 0$ where $\mathbf{z}^1 = DC \cdot \mathbf{x}^1$. They cannot be differentiated with the plan $\mathbf{x}^1$. If the OEM accepts this plan, the supplier can expand common stations. These three steps are an iterative process. The OEM and the supplier repeat this process until they agree to a certain constraint plan. The supplier promises to accommodate diversified DPs on their process and the OEM promises to design derivative components to obey the constraints.

3. **An Illustrative Example of MBR Component.** This study presents a case of an automobile manufacturer (OEM) who outsources production of an MBR component to an external supplier. An MBR is an automotive component that fixes and supports the drive system parts on the rear side of a vehicle body. This component varies between vehicle models because it determines a wheel location and absorbs vibration from the ground. An automotive company (OEM) sources components of all vehicle models from a sole supplier for exploiting economy of scale. If it is fully varied between models, however, the supplier should produce components of each model by independent manufacturing lines. Since it seriously impairs efficiency, they need to collaborate in designing components and their manufacturing processes.

An MBR component is manufactured by welding 17 different steel parts – only 11 parts are unique since six pairs of the parts are symmetrically identical on the left- and right-hand sides (denoted by LH/RH). Their design parameters are simplified by 32 variables for length (L), width (T), height (H), and hole positions (POS), as shown in Table 1. To avoid confusion, this study uses 'component' for denoting MBR, and uses 'part' for denoting its subcomponents. All the detailed numbers have been modified to protect confidentiality.

Step 1: Divide a supplier process into stations. As assumed earlier, the OEM first sources a platform component from the supplier. The supplier constructs a baseline

Table 1. Parts and DPs of MBR

Parts	DPs	Parts	DPs
BRKT ASSY HANGER MUFFLER	H	MBR NO1 UPR	H
BRKT ASSY HANGER MUFFLER	L	MBR NO1 UPR	T
BRKT FR A/ARM MTG LH/RH	T	MBR NO1 UPR	L
BRKT FR A/ARM MTG LH/RH	L	MBR NO1 UPR	POS
BRKT FR A/ARM MTG LH/RH	POS	MBR NO2 FR	H
BRKT RR A/ARM MTG LH/RH	T	MBR NO2 FR	T
BRKT RR A/ARM MTG LH/RH	L	MBR NO2 FR	POS
BRKT RR A/ARM MTG LH/RH	POS	MBR NO2 RR	H
BRKT U/ARM FR LH/RH	T	MBR NO2 RR	T
BRKT U/ARM FR LH/RH	POS	MBR NO2 RR	POS
BRKT U/ARM RR LH/RH	T	MBR SIDE LWR LH/RH	POS
BRKT U/ARM RR LH/RH	POS	MBR SIDE LWR LH/RH	T
MBR NO1 LWR	H	MBR SIDE LWR LH/RH	H
MBR NO1 LWR	T	MBR SIDE UPR LH/RH	POS
MBR NO1 LWR	L	MBR SIDE UPR LH/RH	T
MBR NO1 LWR	POS	MBR SIDE UPR LH/RH	H

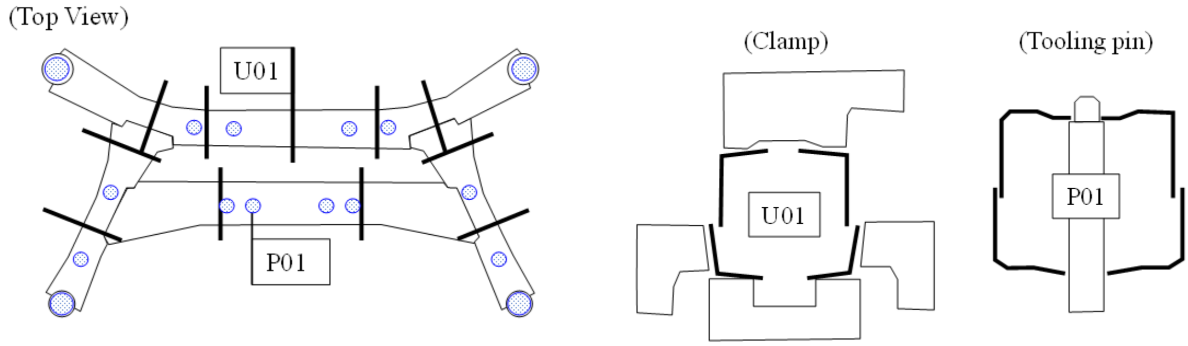
Table 2. Process stations

Name	Description	Labor (# of Resources)	Arc robot (# of Resources)	Transfer robot (# of Resources)	Workbench (# of Resources)
S010	NO1 sub	0	2	1	1
S020	NO1 complete	1	3	0	1
S030	NO2 sub	0	1	1	1
S040	NO2 complete	0	1	1	1
S050	NO1,2 unloading	1	1	0	1
S060	SIDE sub	1	2	0	1
S070	A/ARM sub#1	1	1	0	1
S080	A/ARM sub#2	1	0	0	1
A010	C/MBR key#1	0	1	1	1
A020	C/MBR complete#1	1	2	0	1
A030	C/MBR key#2	0	1	1	1
A040	C/MBR complete#2	1	2	0	1
A050	C/MBR key#3	0	1	1	1
A060	C/MBR cooling#1	1	0	0	1
A070	C/MBR key#4	0	1	1	1
A080	C/MBR complete#3	0	1	1	1

manufacturing process to produce the platform component. Processes for derivative components deviate from this baseline. The supplier first identifies stations from the baseline process. The MBR manufacturing process mostly consists of arc-welding operations. Major resources are workers, welding robots, and handling robots. Table 2 lists the identified stations.

Step 2: Identify process constraints. The major resources of this process, which are robots and workers, are fortunately flexible enough to produce a variety of designs. In contrast, jigs holding a WIP on a workbench are tightly coupled to component design. Thus, jig layouts are identified as process constraints in this case. A jig layout consists of master control points (MCPs) and master control sections (MCSs). Figure 3(a) marks MCPs of the MBR component with spotted circles and solid lines, and Figure 3(b) shows exemplar MCSs of them.

Step 3: Mapping constraints to stations. The constraints are mapped to the identified stations. In the MBR case, fortunately, this mapping is obvious because jigs



(a) MCP (b) MCS

Figure 3. Examples of (a) MCP and (b) MCS

are a part of a workbench. A station has a set of constraints that correspond to jigs of its workbench. They are mapped by a matrix SC.

Step 4: Mapping constraints to DPs. Each constraint, that is a jig layout, fixes DPs at its position. Where a pin-type jig fixes only tooling hole position, which is not a differentiating attribute, a clamp-type jig constrains major dimensions of the MBR component. In Figure 3(b), constraint U01 is a clamp-type jig surrounding subassembly NO1, which is an assembly of parts 'MBR NO1 UPR' and 'MBR NO1 LWR'. Width and height of these components, which are denoted by DPs T and H, respectively, should be fixed if U01 is common for all derivatives.

Step 5: Construct an initial constraint plan. An initial constraint plan is established to make as many stations common as possible while allowing as many DPs varied as possible. Compromising this conflict, initial plan $\mathbf{x}_0$ is chosen to make eleven stations common among sixteen. The DSS indicates that 23 DPs are fixed by this plan, and nine DPs are still free to change, as shown in Figure 2.

Step 6: OEM suggests flexible constraints. The OEM may require more DPs to be differentiated. Assume that they request varying DP (T) of parts 'MBR NO1 UPR' and 'MBR NO1 LWR' to differentiate light and heavy vehicles. Nine stations cannot be common if they become variable. The supplier cannot achieve enough commonality with this plan. They need to make the related constraints flexible. Three constraints S01, U01, and U05 are involved.

Step 7: Supplier suggests variety reduction. In a reverse manner, the supplier requests to reduce variety for sharing more stations. Based on the initial plan $\mathbf{x}_0$, the supplier suggest to additionally share station A050 between derivatives. By this change, DPs (POS) and (T) of 'BRKT U/ARM FR LH/RH' and (POS) of 'BRKT U/ARM RR LH/RH' have to be fixed. The OEM examines whether it is acceptable.

4. **Conclusions and Discussions.** This study proposes a collaborative product and process design procedure between an OEM and a supplier. Where an OEM sources a platform and derivative components from a sole supplier, they both want to maximize commonality of the manufacturing process; the supplier enhances efficiency, and the OEM sources them at a lower price. A key element of this procedure is mapping constraints to manufacturing stations and DPs. The maps systematically identify and manage which DPs are fixed when a station is made common, and which stations cannot be common when a DP is differentiated. The author also developed a DSS to visualize those relationships. The collaborative design procedure was illustrated by a case example of an automotive component.

One hurdle to apply the proposed procedure may be defining constraints in a diverse manufacturing environment. Whereas the illustrated case has jig layouts as obvious constraints, a constraint may be abstract in some cases. It remains as future research to build a library of constraints in a variety of industries and manufacturing processes.

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