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A FRAMEWORK TO SUPPORT CO-DESIGN EXPLORATION OF MANUFACTURING SUPPLY NETWORKS FOR RESILIENCE

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ABSTRACT

Manufacturing Supply Networks (MSNs) involve group decisions to achieve group goals and network decisions to achieve network goals. These decisions are made across multiple levels of a decision hierarchy. Given the frequent disruptions in MSNs, 'resilience' – the ability to maintain satisfactory network functionality despite disruptions, is a vital network goal. When designing MSNs for resilience, the resilience and group goals often conflict, requiring simultaneous consideration of network and group decisions. Limited information in the early stages of MSN design necessitates focusing on design exploration. Hence, facilitating 'co-design exploration' – a simultaneous exploration of network and group solution spaces is crucial.

Current approaches for designing MSNs for resilience do not support simultaneous consideration of network and group decisions. To bridge this gap, we present the ***Co-D****esign* ***E****xploration of* ***M****SNs for* ***R****esilience (CoDE-MR) framework to facilitate co-design exploration of the network and the groups.*

CoDE-MR framework allows designers to model multilevel network and group decisions and their interactions, manage disruptions, and visualize and simultaneously explore the multilevel network and group solution spaces. In the framework, we integrate a combination of Preemptive and Archimedean formulations of the coupled-compromise Decision Support Problem construct with Resilience Index metric and interpretable Self-Organizing Map (iSOM)-based visualization to facilitate co-design exploration of MSNs for resilience. The framework's efficacy is demonstrated using a steel MSN test problem, considering network and group decisions across two levels. The use of information flow and generic constructs makes the framework generic and well-suited for co-design exploration of multilevel systems to ensure resilience.

Keywords: Resilient Design, Co-design, Manufacturing Supply Networks, coupled-compromise Decision Support Problem (c-cDSP), interpretable Self-Organizing Maps (iSOM)

GLOSSARY

Manufacturing Supply Network (MSN): A network of independent, interconnected enterprises that work collectively to physically realize the products and deliver them to customers.
Group: A collection of all the enterprises that perform the same role in the MSN. Example: The collection of all manufacturers that manufacture products required by customers constitute the 'Manufacturer Group.'
Level: Group or groups in the MSN that occupy the same position in a design decision-making hierarchy.
Co-design: A design that facilitates collaboration among a network of stakeholders distributed across multiple levels by supporting the consideration of their interrelations to ensure the satisfaction of the network and stakeholder's goals.
Disruptions: An unplanned or unanticipated event that severely impacts the structure, operations, and performance of MSNs. For example, manufacturing facility shutdowns and supplier closures are disruptions that affect MSNs.
Resilience: The ability of an MSN to maintain satisfactory network functionality in the event of a disruption.
Resilient Design: A design that maintains satisfactory network functionality during a disruption.

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Average Service Level (ASL): A measure of the capability to meet delivery expectations regarding lead times. Mathematically, ASL is defined as the ratio of actual lead time to expected lead time. Actual lead time is computed as the sum of the order processing time and time for transporting raw materials or products from the source to the destination.

1. FRAME OF REFERENCE

Manufacturing Supply Networks (MSNs) comprise independent '*groups*' of enterprises that make '*group decisions*' to realize '*group goals*.' Each group comprises a collection of enterprises that perform the same role in an MSN, such as a manufacturer, supplier, distributor, or customer. Decisions regarding the attainment of *'network goals,'* which define the overall performance of the MSN, are also made in MSNs and are termed '*network decisions*.' These group and network decisions are made across multiple levels of a decision hierarchy and are related by the flow of information and materials, as depicted in Figure 1. Given their importance, network decisions are considered to be made by a group at the top of the decision hierarchy (Group A in Figure 1).

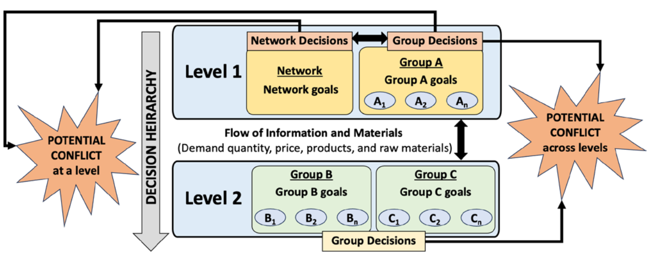

FIGURE 1: Multilevel group and network decisions in MSNs and potential conflicts between these decisions at a level and across levels.

Given the relations among the decisions in an MSN, the group and network decisions impact each other. This can lead to 'conflicts' i) at a level: conflicts between network and Group A decisions at Level 1, as depicted in Figure 1, and ii) across levels: conflicts between group decisions across Levels 1 and 2, see Figure 1. Conflicts occur when the decisions made to realize network goals or a group's goals do not align with the decisions to realize the goals of another group. These conflicts will adversely impact the realization of the network and group goals across multiple levels. Hence, the design of MSNs requires careful consideration of the impact of both network and group decisions on realizing various network and group goals. This necessitates facilitating the '***multilevel co-design*' of the network and groups in MSNs** to satisfy the network and group goals. Multilevel co-design supports i) the *simultaneous consideration of network and group decisions across multiple levels* while accounting for their interactions and ii) the *management of conflicts*.

MSNs are often subject to disruptions, such as supplier closures, production facility shutdowns, and logistics service-provided failures. Disruptions can be either i) *path disruptions* - disruptions affecting the paths connecting the enterprises in an MSN, or ii) *node disruptions* - disruptions affecting the Enterprises (or nodes) in an MSN, as depicted in Figure 2. Node disruptions will subsequently result in the disruptions of incoming and outgoing paths connected to the disrupted node; see paths connected to disrupted node A_n in Figure 2. These disruptions adversely impact MSN performance. Hence, it is vital to ensure the '*resilience*' of MSNs during disruptions. In this paper, we consider resilience as the ability of an MSN to maintain satisfactory network functionality in the event of a disruption. The connectivity among the nodes and redundancy in the network largely influence MSN resilience. Improved resilience can be realized by enhancing redundancy and connectivity via i) having multiple enterprises in each group as alternative nodes in case of node disruptions and ii) having multiple paths connecting the nodes to ensure an alternative path in case of path disruptions. Assuring alternate nodes and paths is vital in ensuring MSN functionality during a disruption. Hence, the design of MSNs requires consideration of resilience as a network goal, with the resilience goal accounting for the presence of both alternative nodes and paths. The requirement is, therefore, the support for '***multilevel co-design of resilient MSNs***' to ensure satisfactory MSN functionality during disruptions.

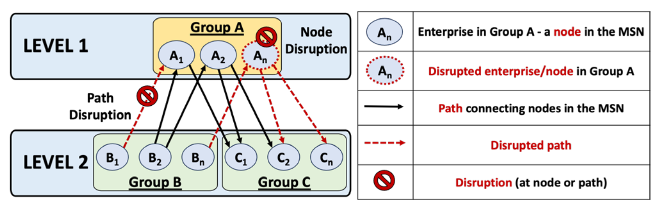

FIGURE 2: Depiction of nodes and paths connecting nodes in an MSN and node and path disruptions and their impact on the MSN connectivity.

Our focus in this paper is on the simulations-supported, **early-stage design** of MSNs where information is limited and models used are incomplete, inaccurate, and not of equal fidelity. When the designer's *focus* during the early stages of design is *on quickly identifying a set of satisfactory solutions*, there arises a need to support the *rapid and simultaneous exploration* of the multilevel solution spaces corresponding to the group and network decisions, termed '***multilevel co-design exploration'*** of resilient MSNs.

We view design from a Decision-based Design (DBD) perspective [1], which is anchored in the '*satisficing*' paradigm proposed by Herbert A Simon [2]. In DBD, design is considered a decision-making process involving compromise and/or selection. Decision Support Problem (DSP) constructs [3] are used to model various decisions in DBD. The compromise Decision Support Problem (cDSP) [4] is a well-established DSP construct that allows designers to model decision problems involving compromises between conflicting goals. Using the cDSP construct, designers identify the '*satisficing solutions'* [5] for the problem by exploring the solutions spaces. Satisficing solutions are ones that 'satisfice' and 'suffice' the designer's requirements for many goals. The coupled cDSP (c-cDSP) [6] is a DSP construct that helps designers model multilevel design problems involving decisions across multiple decision levels.

When using the c-cDSP, the designer focuses on '*minimizing the deviation function.*' The deviation function helps capture the designer's preferences for conflicting goals across multiple levels. The deviation function of the c-cDSP is modeled using the Preemptive and/or Archimedean formulations [4]. The Preemptive formulation helps model preference differences amongst goals at different decision levels. In the Preemptive formulation, goals at different decision levels are assigned different priority levels. The goals at higher priority levels will be realized before those at lower priority levels. The Archimedean formulation allows designers to consider differences in preferences amongst multiple goals at the same decision level. In the Archimedean formulation, the deviation function is modeled as the weighted sum of the deviation variables, with the weights representing the differences in preference among the goals at a level. The deviation variables represent the distance between the set goal target and the actual attainment of the goal.

Existing approaches in the literature to support the design of MSNs for resilience are '*focused on designing the network*' to realize various network goals, including resilience. In doing so, they fail to facilitate the consideration of the impact of i) network decisions on the groups and their goals and ii) group decisions on the network and network goals, specifically during early-stage design exploration. This is the gap that is addressed in this paper. Different approaches to support the design of resilient systems have been proposed in the literature, such as All-in-One (AIO) optimization formulations [7-9] and different Multidisciplinary Design Optimization (MDO) approaches [10]. AIO formulations have been employed extensively in the design of resilient MSNs. The focus when using AIO formulations is on designing the multiple levels of the MSN simultaneously and in an integrated manner. Therefore, AIO formulations fail to account for the independence of the decisions of the various groups in MSNs. AIO formulations also do not facilitate the consideration of the impact of the network decisions on the groups and their goals, and vice versa. Analytical Target Cascading (ATC) - an MDO approach proposed by Kim and co-authors [11] has also been employed to support MSN design [12, 13]. ATC embodies a hierarchical multilevel optimization formulation where each level aims to minimize the discrepancy between the optimal target values calculated at the previous level and the response at the level. Therefore, ATC permits considering decisions across multiple levels and their interactions. ATC and other MDO approaches involve significant iterations within and between multiple decision levels to identify single-point optimum solutions [14], making them computationally expensive. Such computationally expensive MDO approaches are not useful during early-stage design exploration. The MDO approaches, and AIO formulations are based on optimization formulations, where the fundamental assumption is that the models used are complete, all the required information is available, and the objective function is perfect. Given that during the early stages of design, the models employed are incomplete and inaccurate, and the information available is incomplete, our focus is on '*satisficing*' rather than optimizing. Therefore, we seek a range of satisficing solutions rather than a single-point optimum solution.

Different approaches from the satisficing domain have been discussed in the literature that support design exploration to identify satisficing solution sets. Khosrojerdi proposes the Resilient and Structurally Controllable Infrastructure Network (RCIN) method [15] to support the design of resilient infrastructure networks. The RCIN method first involves designing the network structure using the cDSP construct to meet network goals, then designing the network to be structurally controllable to ensure network resilience. The RCIN method focuses on the integrated design of networks to meet various network goals, including resilience. It does not facilitate consideration of the impacts of network decisions on various groups. Nellippallil and co-authors [16] present the Goal-oriented Inverse Design (GoID) approach to support the multilevel co-design of hierarchical process chains involving material, product, and associated manufacturing processes. Using the GoID approach, designers sequentially explore the individual-level solution spaces separately to identify satisficing solutions. These satisficing solutions are then propagated as targets inversely along the hierarchical process chain. Sharma and co-authors [17, 18] propose using coupled DSPs to support the co-design of multilevel engineered systems, which involves interrelated decisions being made hierarchically and/or concurrently. The approach focuses on sequentially exploring the individual design levels to identify satisficing solutions, starting with the level at the top of the design hierarchy. The satisficing solution identified at a level guides the design exploration to identify a solution at the subsequent level. The GoID and coupled DSP-based approaches involve sequential exploration of the individual level solution spaces to identify a ranged set of satisficing solutions for that level. This can result in design conflicts, where solutions identified at one level do not align with those at another. These approaches only allow consideration of goal relations and tradeoffs at a level and do not support the consideration of tradeoffs among the goals across multiple levels of the decision hierarchy. Hence, these approaches require compromises on lower-level goals to satisfy the requirements identified at higher levels, thereby limiting design flexibility during early-stage design exploration. The GoID and coupled DSP-based approaches do not support co-design exploration - the simultaneous exploration of network and group solution spaces across multiple levels. Additionally, solution space visualization and exploration in these approaches are performed using ternary plots that are limited to simultaneously visualizing a maximum of three goals.

In this paper, our focus is on supporting designers in the '*early-stage co-design exploration of MSNs for resilience'* while considering the network and group decisions and their interactions. From a DBD perspective, we hypothesize that early-stage co-design exploration of MSNs for resilience can be realized by facilitating the i) modeling of the multilevel network and group decisions and their interactions in the MSN, ii) management of disruptions by identifying resilient MSN designs that maintain satisfactory network functionality in the event of a disruption, and iii) simultaneous exploration (co-design exploration) of the solution spaces corresponding to the network and group decisions. Towards this, we present a decision support framework, named Co-Design Exploration of MSNs for Resilience (CoDE-MR) framework that supports the: i) modeling of the group and network decisions across multiple levels while considering their interactions in terms of the flow of information, ii) identification of resilient MSN designs by modeling the resilience goal using a resilience metric that accounts for the presence of both alternative nodes and paths (helps reduce the chance of complete loss of MSN functionality in case of disruptions), and iii) simultaneous exploration of the network and groups solution space to identify common satisficing solutions, thereby facilitating co-design exploration of the network and its groups. Given the multilevel network and group decisions, their interactions, and the multiple conflicting goals at each level, we model the multilevel network and group decisions in MSNs using the c-cDSP construct. In the c-cDSP, the deviation function is modeled using a combination of Preemptive and Archimedean formulations. The Preemptive formulation allows the consideration of decisions across different levels, and the Archimedean formulation allows the consideration of multiple conflicting goals at each level. We use the '*Resilience Index*' (RI) metric as the network goal to identify resilient MSN designs. RI is inspired by the gamma index [19], a graph theory-based connectivity metric for network resilience. In RI, the presence of both alternative nodes and paths is considered when computing network resilience. The multilevel solution spaces are visualized in an integrated manner using a machine learning-based visualization tool - interpretable Self Organizing Maps (iSOM) [20], to aid the co-design exploration of the multilevel network and group solution spaces. A detailed discussion of the constructs and tools is presented in Section 3.1.

The outline of this paper is as follows. A description of the problem is presented in Section 2. In Section 3, we present the framework to support the Co-Design Exploration of MSNs for Resilience (CoDE-MR). In Section 4, we use a steel MSN test problem to showcase the framework's efficacy in supporting the co-design exploration of MSNs for resilience while considering the network and group decisions. In the test problem, we focus on the interactions between the network and manufacturer group decisions at Level 1 and supplier group decisions at Level 2. We end the paper with our key findings and closing remarks in Section 5. In Appendix A, we present the design variables and mathematical models that relate the design variables and goals in the c-cDSP formulation for the steel MSN test problem.

2. PROBLEM DESCRIPTION

As discussed in Section 1, MSNs comprise multiple groups that make network and group decisions across multiple levels of a decision hierarchy. Considering an MSN with two levels: i) Level 1, composed of the Manufacturer group with multiple manufacturing facility locations that are indexed as '*j,*' and ii) Level 2, composed of the Supplier group with multiple suppliers that are indexed as 'i' and Customer group with multiple customers that are indexed as '*k,*' as depicted in Figure 3. The design of MSNs involves decisions being made across the two levels. Decisions at Level 1 include network decisions that determine the network structure and the manufacturer group decisions to realize multiple manufacturer group goals. Decisions at Level 2 include supplier and customer group decisions to realize multiple supplier and customer group goals, respectively. The network and group decisions across the levels are interrelated by the flow of information within and between the groups, as described below and depicted in Figure 3. In Figure 3, the flow of information within a level is indicated by solid black arrows, and the dotted red arrows connecting Levels 1 and 2 indicate the flow of information between levels.

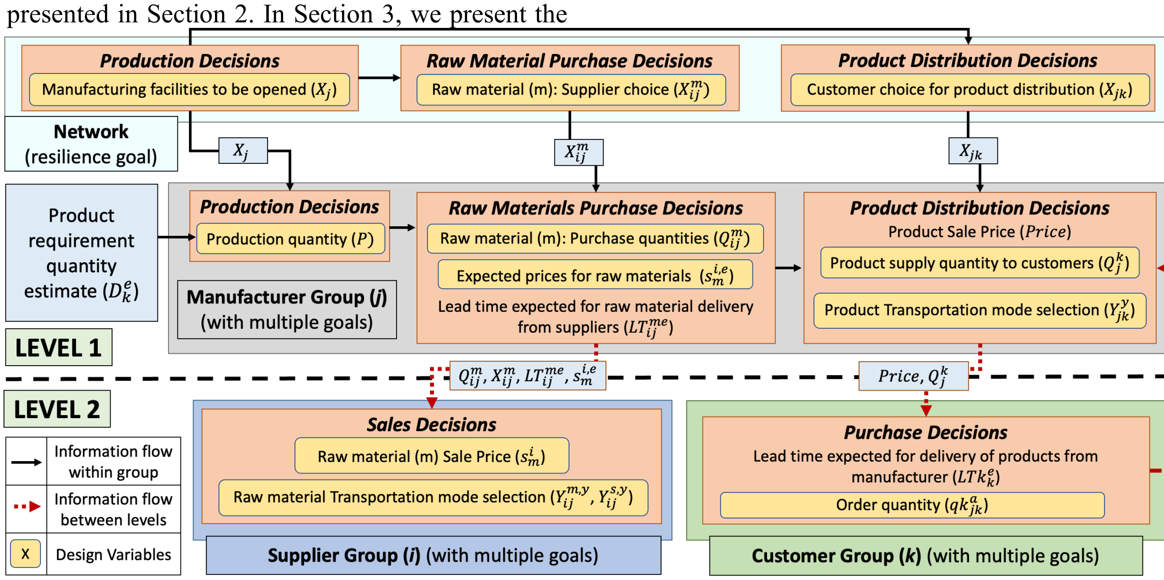

FIGURE 3: Information flow connecting the network, manufacturer group, supplier group, and customer group decisions across two levels (Levels 1 and 2) in a Manufacturing Supply Network (MSN).

At Level 1, network decisions that determined the MSN structure, such as manufacturing facilities to be opened (X_j), Supplier choice for raw material 'm' (X_{ij}^{m}) and Customer choice for product distribution (X_{jk}) are directed towards achieving the resilience goal. At the manufacturer group (j) at Level 1, manufacturer group decisions such as production, the raw material (m) purchase, and product distribution decisions are made based on the estimates of the product requirement quantity (D_k^e) and expected product delivery lead times (LTk_k^e) provided by the customer group, and network decisions (X_j, X_{ij}^{m}, and X_{jk}). The production decision involves estimating the production quantity (P). The raw material purchase decisions include the quantity of raw materials to be procured (Q_{ij}^{m}) and estimated prices at which the raw materials should be purchased (s_m^{ie}). The product distribution decisions include determining the product supply quantities (Q_j^k) and selecting the mode of transportation to deliver the products to customers (Y_{jk}^{y}). These decisions are directed towards realizing the multiple manufacturer group goals. At the supplier group (i) at Level 2, supplier group decisions, such as the choice of mode of transportation of raw materials to the manufacturing facility ($y_{ij}^{m,y}$) and sale prices of raw materials (s_m^i) are made. These decisions are directed towards realizing the multiple supplier group goals. The supplier group decisions are made based on the expected delivery lead times for raw materials (LT_{ij}^{me}) provided by the manufacturer group, $s_m^{i,e}$, and Q_{ij}^{m} values determined by the manufacturer group and the network decision - X_{ij}^{m}. At the customer group (k) at Level 2, the customer group decision related to the purchase of products- quantity of product to be purchased (qk_{jk}^{a}) is made based on the price that the product is sold to the customers by the manufacturer group ($Price$) and the quantity available for sale from the manufacturer group (Q_j^k). The qk_{jk}^{a} decision aims to realize the multiple customer group goals.

Hence, the network, manufacturer group, supplier group, and customer group decisions across Levels 1 and 2 are interrelated by the flow of information, as depicted in Figure 3. Given the relations between network and group decisions across different levels in the MSN, the network and group decisions will impact each other. Hence, the 'multilevel co-design of MSNs for resilience' needs to be facilitated by accounting for the relations between the network and group decisions across multiple levels. Our focus is on exploring the solution spaces during the early stages of MSN design to identify a set of '*satisficing solutions*' for the multilevel network and group goals. This necessitates an approach that aids designers in effectively performing the '*multilevel co-design exploration*' of the multilevel network and group solution spaces. Therefore, there is a need for a systematic approach that supports the '*multilevel co-design exploration of MSNs for resilience*' by facilitating the simultaneous exploration of the network and group solution spaces across multiple levels. The simultaneous exploration will help identify common satisficing solutions that meet the network resilience and group goals.

3. A FRAMEWORK TO SUPPORT CO-DESIGN EXPLORATION OF MANUFACTURING SUPPLY NETWORKS FOR RESILIENCE (CoDE-MR)

In this section, we present the framework to support the **Co**-**D**esign **E**xploration of **M**SNs for **R**esilience (CoDE-MR). We first discuss the various constructs and tools used in the framework. This is followed by a discussion on decision support using the framework.

3.1 Constructs and tools used in the CoDE-MR framework

In the CoDE-MR framework, we use three major constructs/tools, namely the c-cDSP construct, graph theory-based connectivity metric for network resilience - Resilience Index (RI), and a machine learning-based visualization tool - interpretable Self-Organizing Map (iSOM). They are discussed in detail below.

3.1.1 The coupled-cDSP (c-cDSP) construct.

The c-cDSP [6] is a DSP construct that aids designers in considering the relations among decisions that involve making compromises among multiple conflicting goals. The c-cDSP helps model multiple decisions that are hierarchically or concurrently related. This is realized using a combination of the Preemptive and Archimedean formulations [4] for the deviation function of the c-cDSP.

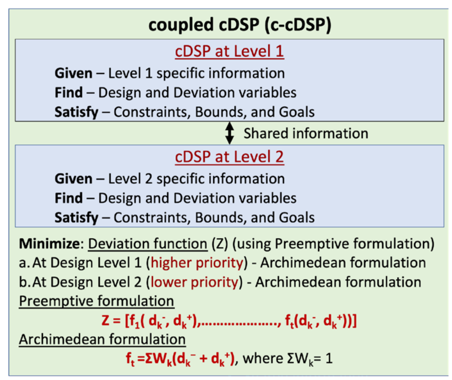

FIGURE 4: The structure of the c-cDSP construct.

The Preemptive formulation allows consideration of hierarchically related decisions across multiple levels of a decision hierarchy. In the Preemptive formulation, decisions at different levels are assigned different priorities, with higher priority levels assigned to decisions higher up in the decision hierarchy, see Figure 4. Correspondingly, the goals at the higher priority levels are realized first before goals at subsequently lower levels. The Archimedean formulation allows the consideration of concurrently related decisions at the same level in a decision hierarchy. It also allows designers to account for multiple goals at the same level. In the Archimedean formulation, designers assign different weights to all the goals across many concurrently related decisions at the same level. The weights are values between 0 and 1 (summing up to 1) and signify differences in preferences amongst the goals at a level. By combining the Preemptive and Archimedean formulations, designers can simultaneously consider decisions across multiple levels and multiple decisions and many conflicting goals at the same level. In the c-cDSP, the information specific to decisions at a level is captured using the '*Given, Find, and Satisfy*' keywords, see Figure 4. When using the c-cDSP, the designers focus on minimizing the 'deviation function' modeled using a combination of the Preemptive and Archimedean formulations, as discussed previously. Mathematically, the deviation function is an ordered set of weighted sum functions of deviation variables across different priority levels. In the proposed CoDE-MR framework, we use the c-cDSP construct to model the multilevel network and group decisions with multiple conflicting goals at each level.

3.1.2 Resilience Index (RI) metric

MSNs are groups of '*nodes*' (enterprises within a group) connected by '*paths*' for the flow of materials or information, as depicted in Figure 5. MSNs are impacted by '*disruptions*' at the nodes - '*node disruptions'* or paths connecting the nodes –' *path disruptions'* [15]. Node disruptions lead to the failure of paths originating from or terminating at the disrupted node, as depicted in Figure 5. These disruptions affect the continuity of the flow of materials in MSN, thereby impacting MSN functionality and performance. Hence, it is vital to ensure MSN '*resilience*'. In this paper, we consider resilience as the ability of an MSN to maintain satisfactory network functionality in the event of a disruption. To ensure resilience, it is crucial to have sufficient alternate nodes and paths. Having multiple paths between nodes improves accessibility and minimizes the isolation of nodes in case of a path disruption. Incorporating alternative nodes creates alternate connections in MSNs, thereby enhancing redundancy to improve '*connectivity'* and overall MSN functionality. Hence, we use network connectivity in MSNs to indicate its resilience.

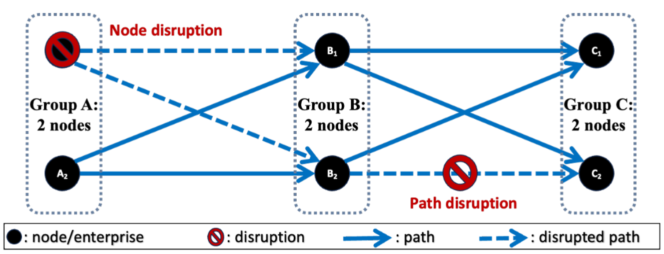

FIGURE 5: An MSN design configuration with multiple nodes at and across multiple groups and the multiple paths connecting the nodes. Situations of node and path disruptions and their impact on connectivity in the MSN are depicted.

The importance of connectivity in ensuring the resilience of networks can be explained using the following example. Consider an MSN design configuration with multiple nodes within each group and multiple paths connecting the nodes, as depicted in Figure 5. Disruption of a node and path does not result in the total loss of connectivity among Groups A, B, and C, thereby helping retain the MSN functionality, which depicts the 'resilience of the MSN' to path and node disruptions. This resilience of the MSN is attributed to the presence of alternative paths and nodes that help sustain connectivity in the MSN during a disruption.

Graph theory provides a framework for calculating connectivity in networks – a network topological characteristic. The gamma index [19] is a graph theory-based measure that helps quantify network connectivity. It represents the ratio of the actual number of paths to the maximum possible number of paths in the network. The value of the gamma index ranges from 0 to 1, with a higher value representing greater network connectivity and, thereby, higher resilience. In the gamma index, the maximum possible number of paths in the network is computed as 3(n-2), where 'n' represents the number of nodes in the network. During MSN design, 'n' is considered as a design variable. By using the varying values of 'n' to compute the gamma index for different MSN designs, the gamma index fails to account for the impact of having alternate nodes (indicated by larger 'n' values) on resilience. Hence, we propose a connectivity metric – *Resilience Index* (RI), inspired by the Gamma index. As with the gamma index, RI represents the ratio of the actual number of paths to the maximum possible number of paths in the network. In RI, the maximum possible number of paths in the network is computed as 3(n-2), with 'n' being a constant value – *the maximum number of possible nodes in the network*. By considering 'n' equal to the maximum number of possible nodes in the network, we can measure connectivity in the network as compared to the ideal case that ensures maximum resilience – the case where all possible nodes and paths exist. Hence, we can also account for the effect of having alternate nodes using RI. Additionally, RI can be used to compare the resilience of different MSN designs and make network design decisions. The mathematical formula for computing RI is provided in Equation 1.

$$\text{RI} = \frac{Actual\ number\ of\ paths\ in\ the\ network\ (A)}{Maximum\ \ possible\ number\ of\ paths\ in\ the\ network\ (M)} \tag{1}$$

where,

$M = 3\,(\text{nodes} - 2)$

nodes = Maximum number of possible nodes in the network structure (a constant value)

As an example, the computation of RI for the MSN configuration depicted in Figure 5 follows. For the MSN in Figure 5, n = 6, the sum of the number of nodes in Groups A, B, and C. For the MSN disrupted by the node and path disruptions, A = 5 (considering the solid blue arrows). Therefore, M = 3(6-2) = 12 and RI = 5/12 = 0.416. The maximum RI value for the given configuration is achieved when all paths exist, where A = 8 (considering all blue arrows). This will result in an RI = 8/12 = 0.67. In this CoDE-MR framework, we employ the RI metric to model network decisions. The network decisions aim to maximize the RI value to ensure MSN resilience. Using RI as a network goal allows designers to realize resilient MSN designs where alternate nodes and paths exist.

3.1.3 interpretable Self-Organizing Maps (iSOM)

iSOM [20] is a machine learning technique, precisely, an artificial neural network (ANN) technique used to represent highly intricate multi-dimensional data through 2D plots visually. iSOM is derived from the traditional Self-Organizing

Maps (SOM) [21] initially developed by Kohonen. In the case of iSOM, modifications have been introduced to avoid issues such as self-intersection, thereby enhancing the interpretability of the resulting iSOM plots. One of iSOM's notable strengths is its adeptness at navigating the complex design spaces inherent in real-world scenarios. This is primarily due to its scalability and interpretive capabilities. The plots generated by iSOM play a crucial role in uncovering the underlying correlations among i) input design parameters and resulting output responses and ii) output responses.

The utility of the iSOM tool in visualizing high-dimensional design spaces and understanding the relationships between inputs and outputs in multilevel systems is discussed in the works by Sushil and co-authors [22] and Baby and co-authors [23]. In the proposed CoDE-MR framework, iSOM facilitates the co-design exploration of multilevel network and group solutions spaces in MSNs. This is realized by concurrently visualizing the solution spaces corresponding to multiple decisions across multiple levels using iSOM plots. The iSOM tool is conveniently accessible as a MATLAB code [20].

3.2 Decision support using the CoDE-MR Framework

The use of the CoDE-MR framework is described in this section. The framework is executed in three steps, as depicted in Figure 6. Each of these steps is described in detail below. We only consider the interactions between two levels in the framework to demonstrate the idea.

- <u>*Step 1*</u>: The designer models the multilevel network and group decisions (at two levels, Levels 1 and 2) and their interactions using the c-cDSP construct. Towards this, the designer begins by collecting information specific to decisions at the levels and their relations using three sub-steps: Steps 1a, 1b, and 1c.
- *Step 1a*: The designer begins by collecting information specific to the decisions at Level 1. At Level 1, the decisions related to realizing the '<u>network resilience goal</u>' and '<u>the goals of the group/groups at the level</u>' are considered. The collected information includes the **<u>network goal</u> – *modeled using the Resilience Index (RI) metric*** and group goals, their target values, design variables and bounds, constraints, and other information specific to the level.
- *Step 1b*: The designer then collects information specific to the decisions at Level 2. At Level 2, the decisions related to realizing the '<u>goals of the group/groups at the level</u>' are considered. The information collected includes the group goals and goals target values, design variables and their bounds, constraints, and other level-specific information.
- *Step 1c*: Next, the designer focuses on establishing the relations between the decisions at and across levels in terms of the flow of information. At Level 1, the information connecting the network and group decisions is identified. This helps establish the relations among the network and group decisions at the level. The information shared between Levels 1 and 2 is determined to establish the relations between the levels.

  Using the information collected in Steps 1a, 1b, and 1c, the designer models the multilevel network and group decisions and their interactions in the MSN using the c-cDSP construct. Next, this c-cDSP formulation is executed for different multilevel design scenarios in Step 2.

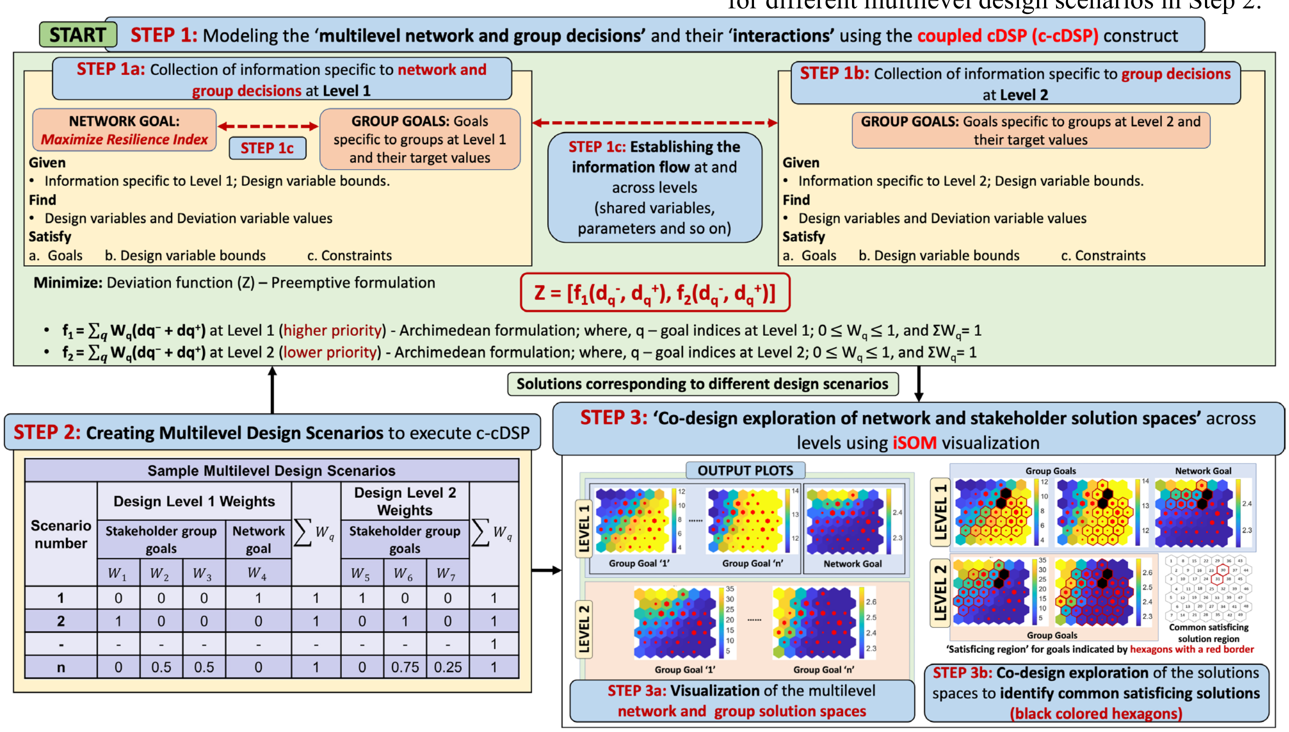

FIGURE 6: **Framework to support Co-Design Exploration of MSNs for Resilience (CoDE-MR)**

- *Step 2*: The c-cDSP formulated in Step 1 is executed for different multilevel (two) design scenarios to generate multiple design solutions, as shown in Step 2 of Figure 6. The multilevel design scenarios are created by combining individual-level design scenarios in all possible combinations. Therefore, in a case where 'n' individual-level design scenarios are considered across 'm' levels, 'n*m' multilevel design scenarios will exist. The individual-level design scenarios represent different combinations of weights assigned to all the goals at a level, including network and group goals. The weights (values between 0 and 1) in each design scenario represent differences in preferences among the goals at the level, with larger weight values depicting higher preferences. Next, in Step 3, the multiple design solutions are visualized for co-design exploration.
- *Step 3*: In this Step, the solutions spaces corresponding to the design solutions generated in Step 2 are visualized and simultaneously explored using the iSOM tool. This is carried out in two sub-steps: Steps 3a and 3b.
  - *Step 3a*: To begin, iSOM is trained using a dataset composed of the multilevel design scenario weights and the corresponding network and group goal values across the two levels. At the end of the training process, iSOM outputs separate 2D plots for the network and group goals across the two levels, as shown in Step 3a of Figure 6.
  - *Step 3b*: Using the iSOM goal plots generated in Step 3a, the designer carries out co-design exploration – the simultaneous exploration of the network and group solution spaces across multiple levels, to identify common satisficing solutions. The designer begins by setting satisficing limits for each network and group goal to identify '*satisficing solution regions for each goal*,' as depicted in Step 3b of Figure 6. Only iSOM grid points with design solutions mapped against them (hexagonal grids with red points at the center) are considered part of the satisficing solution region.

    The designer then checks for a common satisficing solution region on the iSOM plots for all goals. If a common region cannot be identified, the designer systematically relaxes the satisficing limits for individual goals till a common solution region is identified. The systematic relaxation of satisficing limits begins with the identification of a critical goal whose limit cannot be relaxed (typically the RI goal). The designer relaxes the limits of the remaining non-critical goals one at a time till a common solution region is identified with the critical goal. The designer relaxes the non-critical goals in the order of decreasing scope of relaxation as determined by the designer, starting with the goal having the most considerable scope of relaxation.

At the end of Step 3b, the designer identifies common satisficing solution regions for the network and group goals, and the design solutions mapped to these regions. Hence, using the CoDE-MR framework, designers can carry out co-design exploration to simultaneously realize the network resilience goal (for resilient MSN design) and group goals across multiple levels.

4. TEST PROBLEM: STEEL MANUFACTURING SUPPLY NETWORK (MSN)

The test problem considered is a steel MSN composed of the manufacturer, supplier, and customer groups across two levels – Levels 1 and 2, as depicted in Figure 7. Level 1 comprises the steel manufacturer group (j) with two steel manufacturing enterprises ($j = 1, 2$) that produce steel slabs. Level 2 comprises: i) the supplier group, composed of the two supplier enterprises ($i = 1, 2$) that supply the raw material - coal ($m = 1$) required for steel production, and ii) the customer group, composed of the two customers ($k = 1, 2$) for the steel slabs produced by the manufacturer. The steel manufacturer group at Level 1 purchases coal from the supplier enterprises in the supplier group at Level 2 to produce steel slabs. These steel slabs are sold directly to the customers in the customer group at Level 2. The steel production quantity is determined based on an estimate of expected customer demand, which is assumed to be known. It is also assumed that both manufacturing enterprises ($j = 1, 2$) employ the integrated Blast Furnace (BF) – Basic Oxygen Furnace (BOF) technology for steel production [24, 25]. The customers in the customer group at Level 2 purchase steel slabs from the manufacturers. Hence, the groups across the levels in the steel MSN are related by the flow of materials (products and raw materials) via the paths depicted in Figure 7. This material flow is facilitated by employing logistics services, the cost for which is borne by one of the interacting groups. In this test problem, we consider two choices for the modes of transportation between the groups: a) Road (faster but relatively expensive) and b) Rail (less expensive but slower).

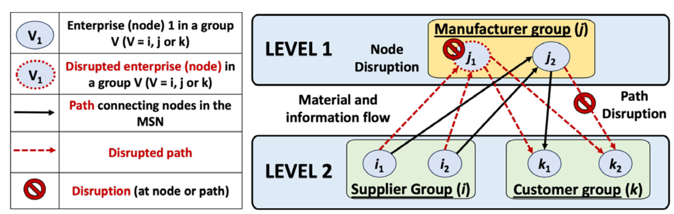

FIGURE 7: Paths connecting the enterprises (nodes) in the manufacturer, supplier, and customer groups across Levels 1 and 2 in the steel MSN.

The steel MSN is exposed to various path and node' *disruptions.*' Node disruptions occur at the enterprises in a group and will result in the failure of all incoming and outgoing paths. Hence, node disruptions will impact the group where the disruption occurs and the connected groups. For example, in Figure 7, disruption of node 'j_1' due to facility breakdown results in the failure of all paths to and from the node. Hence, the node disruption directly impacts the manufacturer, supplier, and customer groups - manufacturers lose production capacity, suppliers are impacted by reduced raw material demand, and customers are impacted by reduced availability of products. Path disruptions can also occur on paths connecting the enterprises in different groups. Path disruptions impact the groups connected by the path. For example, the path disruption depicted in Figure 7 will directly impact the manufacturer and customer groups - manufacturers lose revenue from product sales, and the reduced availability of products impacts customers. Given the impact of disruptions on the various groups, it is vital to consider resilience as a network goal during the design of the steel MSN.

At Level 1 in the steel MSN, decisions are made by the manufacturer group to realize the manufacturer group-specific goals, see Figure 8. Decisions at Level 1 also include the 'network decisions' such as the choice of nodes and paths connecting the nodes in the network. The network decisions determine the network structure and influence the steel MSNs resilience. At Level 2, the supplier and customer groups make decisions to meet their respective group goals. Hence, the steel MSN is characterized by '*multilevel network and group decisions'* made across Levels 1 and 2. The multilevel group and network decisions are related through the flow of materials and information, as depicted in Figure 8. Given these relations, the network and group decisions will affect each other. Therefore, it becomes vital to consider the *'interactions at and across multiple levels*.' The interactions among the multilevel network and group decisions can result in *conflicts*, where the decisions made to realize the network resilience goal or a group's goals do not align with the decisions to realize the goals of another group. The conflicts will adversely impact the realization of the network and group goals; hence, there is a need to manage the conflicts to ensure steel MSN performance. This requires the facilitation of '*multilevel co-design*' of the network and groups in the steel MSN to ensure resilience. In the early stages of the steel MSN design, the focus is on design exploration to identify a set of satisficing solutions. This necessitates focusing on '*multilevel co-design exploration*' of the network and groups in the steel MSN to ensure resilience.

In this paper, we demonstrate the utility of the CoDE-MR framework in facilitating the multilevel co-design exploration of the network and groups in MSNs to ensure resilience by considering the interactions between the network decisions, manufacturer group decisions, and supplier group decisions across Levels 1 and 2. We consider decisions made hierarchically in the steel MSN, with the manufacturer group being the lead decision maker. Hence, the manufacturer group makes the manufacturer group and network decisions at Level 1, and the supplier group makes supplier group decisions at Level 2.

4.1 Decisions made across multiple levels in the steel MSN and their interactions.

The description of the network and group decisions made at Levels 1 and 2 and their interactions at and across levels are discussed below.

4.1.1 Decisions made by the manufacturer group at Level 1

The manufacturer group manufactures products per customer requirements using raw materials sourced from the suppliers. The manufactured products are delivered to the customers directly from the manufacturers. Hence, the manufacturer group at Level 1 interacts directly with the supplier and customer groups at Level 2. These interactions are represented by the information flows, as depicted in Figure 8. The arrows within the manufacturer group depict the flow of information within the group. The arrows connecting Levels 1 and 2 depict information flow from external sources, including other interacting groups. The manufacturer group makes production, materials sourcing, and product distribution decisions (see manufacturer group at Level 1 in Figure 8). These decisions are aimed at fulfilling three group-specific goals: i) G_1 - minimization of Average Service Level (ASL) to customers, ii) G_2 - maximization of manufacturer group profit, and iii) G_3 - minimization of greenhouse gas (GHG) emissions by the manufacturer group. These goals are conflicting - a focus on minimizing the ASL results in reduced profits and increased GHG emissions. The values indicated in the dashed yellow boxes at the manufacturer group in Figure 8 depict the manufacturer group design variables.

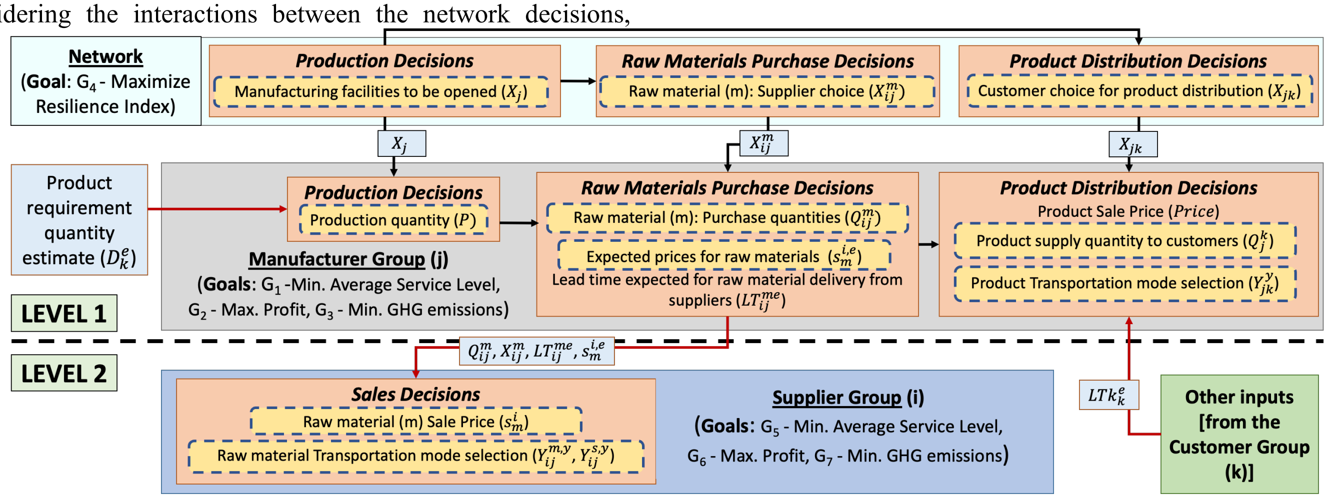

FIGURE 8: Information flow connecting the network decisions, manufacturer group decisions, and supplier group decisions across Levels 1 and 2 in the steel MSN

The assumptions for decisions made by the manufacturer group at Level 1 are listed below.

a) The manufacturer employs the Made-to-Stock (MTS) approach to manufacturing, making products based on an estimate of customer demand.
b) The manufacturer bears the cost of transportation of products to customers.
c) There is sufficient capacity at the suppliers to meet the manufacturer's demand.
d) All modes of transportation have sufficient capacity to supply the required quantity of products together.

Next, we describe the network decisions made at Level 1.

4.1.2 Network decisions at Level 1

Network decisions are considered at Level 1 as they determine the steel MSN structure. As the lead decision-maker, the manufacturer group makes the network decisions at Level 1 that are directed toward realizing the network goal.

Since ensuring steel MSN performance under disruptions is vital, network resilience is considered the network goal. The network resilience is quantified using the Resilience Index (RI) metric discussed in Section 3.1.2. Hence, the network decisions at Level 1 are directed towards realizing goal G_4 - maximizing RI. The network decisions include a binary (0 or 1) choice of i) manufacturing facilities to be opened, ii) suppliers to source raw material 'm', and iii) customer choice for product distribution. These network decisions collectively determine the RI value. The network decisions directly interact with and influence the manufacturer group decisions at Level 1. For example, the choice of manufacturing facilities to be opened directly influences the quantity of products produced at each facility. These interactions are represented by the information flows between the network and manufacturer group at Level 1, as depicted in Figure 8. The black arrows within the network decisions depict the interactions within network decisions. For example, the choice of manufacturing facilities to be opened directly influences the supplier's choice to source raw materials for a facility and the paths connecting them. Next, we describe the supplier group decisions made at Level 2.

4.1.3 Decisions made by the supplier group at Level 2

The supplier group at Level 2 supplies the required raw materials (coal, $m = 1$) to the manufacturers in the manufacturer group according to the demand. Hence, the supplier group interacts only with the manufacturer group at Level 1. These interactions are represented by the information flows, as depicted in Figure 8. The arrow flowing into the supplier group depicts information flow from the manufacturer group at Level 1. The decisions by the supplier group at Level 2 are aimed at fulfilling three supplier-specific goals: i) G_5 - minimization of Average Service Level (ASL) to manufacturers, ii) G_6 - maximization of supplier group profit, and iii) G_7 - minimization of greenhouse gas (GHG) emissions by the supplier group. These goals are conflicting in nature, as discussed previously in Section 4.1.1. The values indicated in the dashed boxes at the supplier group in Figure 8 depict the supplier group design variables. The assumptions for decisions made by the supplier group at Level 2 are as follows:

a) There exists sufficient capacity at all the suppliers to meet the manufacturer's demand for coal.
b) The suppliers bear the cost of transporting raw materials to the manufacturer.
c) All modes of transportation have sufficient capacity to supply the required quantity of raw material (coal) together.

The manufacturer and supplier groups at Levels 1 and 2 in the steel MSN are related by the '*shared design variables'* - prices for the coal raw material, and '*propagated parameters'* - raw material purchase quantities and expected lead times for raw materials supply, as depicted by the red arrow connecting the manufacturer and supplier groups in Figure 8.

4.2 Steel MSN: Decision support using the CoDE-MR framework

We demonstrate the CoDE-MR framework's utility in supporting the multilevel co-design exploration of the network and groups to ensure MSN resilience by applying it to the steel MSN test problem described in Section 4.1. The designer begins at Step 1, where the multilevel network and group decisions and their interactions are modeled using the c-cDSP construct.

4.2.1 Step 1

The designer begins the Step by collecting the information specific to the decisions at Levels 1 and 2 in Steps 1a and 1b, respectively.

i. <u>Step 1a</u>: At Level 1, at the top of the hierarchy of decisions, the manufacturer group makes i) group decisions to meet its goals and ii) network decisions to ensure steel MSN resilience. The information specific to Level 1 includes:
   a) <u>Manufacturer group (j) decision information</u>:
   - Manufacturer group design variables (12 continuous and 8 binary variables) and their bounds. <u>All binary variables are modeled as continuous variables</u> using '<u>*binary reformulation*</u>' as discussed in [26]. A '*binary variable relaxation constraint*' is added for each binary variable to ensure that their values are either 0 or 1. Details of the variables are provided in Appendix A1.
   - Manufacturer goals (G_i) and targets: G_1 - Minimize Average Service Level (ASL) to customers (target: 0.5), G_2 - Maximize manufacturer group profit in \$ (target: \$900,000), and G_3 - Minimize total GHG emission by the manufacturer group in kg of CO_2 (target: 950,000 kg). The mathematical models for these goals are provided in Appendix A2.
   - Manufacturer group constraints (30 constraints)
     1. The total production quantity should be less than the maximum demand (assuming a +5% buffer)
     $$\sum_{j=1}^{2} P_j \leq 1.05\left(\sum_{k=1}^{2} D_k^e\right)$$
     2. The total production quantity should exceed the minimum demand (assuming a -5% buffer).

$$\sum_{j=1}^{2} P_j X_j \geq 0.95(\sum_{k=1}^{2} D_k^e)$$

3. The amount of coal (m = 1) purchased at each location should meet the requirement (assuming a ±5% buffer).

$$0.95 A_m P_j X_j \leq \sum_{i=1}^{2} Q_{ij}^m X_{ij}^m \leq 1.05 A_m P_j X_j, \text{ for } m = 1 \text{ and } j = 1,2$$

4. The maximum quantity of coal supplied from a supplier to all manufacturing locations should be less than the supplier's capacity.

$$\sum_{j=1}^{2} Q_{ij}^m X_{ij}^m \leq 3000 \text{ for } i = 1,2$$

5. The total product supply quantity from each manufacturer facility must be below production.

$$\sum_{k=1}^{2} Q_j^k X_{jk} \leq P_j X_j, \text{ for } j = 1,2$$

6. The total quantity of products supplied to each customer must meet the demand (assuming a ±5% buffer).

$$0.95 D_k^e \leq \sum_{i=1}^{2} Q_j^k X_{jk} \leq 1.05 D_k^e, \text{ for } k = 1,2$$

7. Only one mode of transportation can be selected for product transportation (with a ±5% violation tolerance)

$$0.05 \geq \sum_{y=1}^{2} Y_{jk}^y - X_{jk} \geq -0.05, \text{ for all } j = 1,2 \text{ and } k = 1,2$$

8. Binary variable relaxation constraints

$$Y_{jk}^y (Y_{jk}^y - 1) = 0, \text{ for all } j = 1,2, k = 1,2, \text{ and } y = 1,2$$

- Other information relevant to manufacturer group decisions, as provided in Appendix A4.

b) Network decision information:

- Network design variables (10 binary variables) and their bounds. All binary variables are modeled as continuous variables, with '*binary variable relaxation constraints*' being added. Details of the variables are provided in Appendix A1.
- Network goal (G_i) and target: G_4 - Maximize Resilience Index (target: 1). The mathematical model for this goal is provided in Appendix A2.
- Network constraints (17 constraints):
  1. At least one manufacturing facility needs to be opened.

$$\sum_{j=1,2} X_j \geq 1$$

  2. At least one supply path should exist for each customer (k) from the manufacturers (j)

$$\sum_{j=1,2} X_{jk} \geq 1, \text{ for all } k = 1, 2$$

  3. Restriction on the maximum number of paths from manufacturer (j) to customers (k)
     For all j = 1, 2:

$$\text{if } (X_j = 0), \sum_{k=1,2} X_{jk} = 0$$
$$\text{else, } \sum_{k=1,2} X_{jk} \geq 1$$

  4. Restriction on the maximum number of paths to manufacturer (j) from to suppliers (i)
     For all j = 1, 2:

$$\text{if } (X_j = 0), \sum_{i=1,2} X_{ij} = 0$$
$$\text{else, } \sum_{i=1,2} X_{ij} \geq 1$$

  5. Binary variable relaxation constraints

$$X_j(X_j - 1) = 0, \text{ for all } j = 1,2$$
$$X_{ij}(X_{ij} - 1) = 0, \text{ for all } i = 1,2, j = 1,2$$
$$X_{jk}(X_{jk} - 1) = 0, \text{ for all } j = 1,2, k = 1,2$$

- Other information relevant to network decisions, as provided in Appendix A4.

ii. Step 1b: At Level 2, the supplier group makes group decisions to meet its goals. The information specific to Level 2 includes:

Supplier group (i) decision information:

- Supplier group design variables (2 continuous and 8 binary variables) and their bounds. All binary variables are modeled as continuous variables, with *binary variable relaxation constraints*' being added. Details of the variables are provided in Appendix A1.
- Supplier goals (G_i) and targets: G_5 - Minimize Average Service Level (ASL) to the manufacturer (target: 0.2), G_6 - Maximize total supplier group profit in \$ (target: \$300,500), and G_7 - Minimize total GHG emission by the supplier group in kg of CO_2 (target: 1,550 kg). The mathematical models for these goals are provided in Appendix A3.
- Supplier group constraints (20 constraints):
  1. The maximum and minimum value for shared design variables, s_m^i. (*Shared design variable relaxation constraints*: Assuming + 5 % relaxation)

$$s_1^{1e} \leq s_1^1 \leq 1.05 s_1^{1e}$$
$$s_1^{2e} \leq s_1^2 \leq 1.05 s_1^{2e}$$

  2. Only one mode of transportation can be selected for coal (m =1) transportation (with a 5% violation tolerance):

$$0.05 \geq \sum_{y=1}^{2} Y_{ij}^{my} - X_{ij}^m \geq -0.05, \text{ for all } j = 1,2; i = 1,2 \text{ and } m = 1$$

  3. Binary variable relaxation constraints

$$Y_{ij}^{my}(Y_{ij}^{my} - 1) = 0, \text{ for all } i = 1,2, j = 1,2, y = 1,2 \text{ and } m = 1$$

- Other information relevant to supplier group decisions, as provided in Appendix A5.

Given the information specific to the decisions at Levels 1 and 2, the designer proceeds to Step 1c.

iii. Step 1c: In this Step, the designer models the interactions among the decisions at and across Levels. At Level 1, there exists propagation of network decisions to the manufacturer group. There also exists a flow of information between the manufacturer group at Level 1 and the supplier group at Level 2, as depicted in Figure 9.

Using the information collected in Steps 1a, 1b, and 1c, the designer formulates the multilevel network and group decisions and their interactions in the steel MSN using the c-cDSP construct.

The '*c-cDSP word formulation*' for the steel MSN design problem is provided below.

Given

a) Information relevant to network and manufacturer group decisions at Level 1: Network, Manufacturer, and Customer group information. (see Appendix A4 for details)
Information relevant to supplier group decisions at Level 2: Network, Manufacturer, and Supplier group information. (see Appendix A5 for details)

b) Design variables and their bounds (see Appendix A1 for details)
   - At Level 1: Network decision variables (10 binary) and manufacturer group decision variables (12 continuous and 8 binary)
   - At Level 2: Supplier group decision variables (2 continuous and 8 binary)

c) Goals at Level 1 (G_i): Manufacturer group goals: G_1, G_2, G_3, and Network goal: G_4.
Goals at Level 2 (G_i): Supplier group goals: G_5, G_6, and G_7.

Find

At Level 1: Values of

a) Design variables: (12 continuous and 18 binary variables)

b) Deviation variables: $(d_i^+,\ d_i^-)$ for all $i = 1, 2, 3, 4$

At Level 2: Values of

a) Design variables: (2 continuous and 8 binary variables)

b) Deviation variables: $(d_i^+,\ d_i^-)$ for all $i = 5, 6, 7$

Shared Design variables: $\boldsymbol{s_m^{ie}}$ and $\boldsymbol{s_m^{i}}$ are the shared design variables between the levels. $\boldsymbol{s_m^{i}}$ is a copy of $\boldsymbol{s_m^{ie}}$ at the supplier group (Level 2)

Satisfy

At Level 1

a) 47 constraints

b) Design variable bounds for all 30 design variables.

At Level 2

a) 20 constraints

b) Design variable bounds for all 10 design variables.

Minimize

Deviation function, Z: a combination of Preemptive and Archimedean formulation.

Level 1 is at higher priority - Priority 1, and Level 2 is at lower priority - Priority 2.

$$Z = [\ f_1, f_2\ ]$$

where,

f_1 and f_2 are the Archimedean formulations at Levels 1 and 2, respectively.

$$f_1 = \sum_{q=1}^{4} W_q\ (d_q^+ + d_q^-) \text{ where } \boldsymbol{\Sigma}\ W_q = 1 \text{ and } q = 1, 2, 3, 4$$

$$f_2 = \sum_{q=5}^{7} W_q\ (d_q^+ + d_q^-) \text{ where } \boldsymbol{\Sigma}\ W_q = 1 \text{ and } q = 5, 6, 7$$

4.2.2 *Step 2*

The multilevel design scenarios for executing the c-cDSP formulation are created using a uniform sampling across Levels 1 and 2. A total of 169 design scenarios are created. The c-cDSP formulation for the steel MSN problem established in Step 1 (see Section 4.2.1.) is then executed for these 169 design scenarios. Some sample design scenarios are listed in Table 1.

TABLE 1: Sample Multilevel Design Scenarios

Design Scenario #	Level 1 Weights				$\boldsymbol{\Sigma}\ W_i$	Level 2 Weights			$\boldsymbol{\Sigma}\ W_i$
	W_1	W_2	W_3	W_4		W_5	W_6	W_7	
1	1	0	0	0	1	1	0	0	1
2	1	0	0	0	1	0	1	0	1
-	-	-	-	-	-	-	-	-	-
55	0.5	0.5	0	0	1	0	0	1	1
56	0.5	0.5	0	0	1	0.5	0.5	0	1
-	-	-	-	-	-	-	-	-	-
168	0.25	0.25	0.25	0.25	1	0.2	0.2	0.6	1
169	0.25	0.25	0.25	0.25	1	0.33	0.34	0.33	1

Next, the solutions generated by executing the c-cDSP formulation are visualized using iSOM in Step 3.

4.2.3 *Step 3*

The designer starts with Step 3a, where the design scenario weights and the solutions generated by executing the c-cDSP are used to train iSOM. The trained iSOM outputs separate 2D iSOM plots for each group and network goal across multiple levels. Next, the designer uses these plots to perform '*co-design exploration of the network and group solutions spaces'* in Step 3b. Co-design exploration begins with the designer setting satisficing limits for each goal to identify satisficing solution regions for the multilevel network and group goals, as depicted in Figure 9. The initial satisficing limits for each goal, as specified, are as follows.

At Level 1

$G_1 \leq 1$; $G_2 \geq$ \$ 600,000; G_3: $\leq$ 1,150,000 kg; $G_4 \geq 0.5$

At Level 2

$G_5 \leq 1$; $G_6 \geq$ \$ 130,000; $G_7 \leq$ 21000 kg

With the satisficing limits set to the above values, no common regions are identified for all seven goals across Levels 1 and 2. Hence, the designer systematically relaxes the limits until a common satisficing region is identified.

The designer identifies the network goal (G_4) - the Resilience Index, as the critical goal whose satisficing limit cannot be relaxed. The designer relaxes the satisficing limits for the remaining non-critical goals one at a time. The designer starts with G_2, which is deemed to have the most considerable scope for relaxation. The satisficing limit for G_2 is relaxed to \$480,000 to identify two common grid points (hexagons in the iSOM plots) with G_4. Next, the satisficing limit of G_3 is relaxed to 1,180,000 kg, followed by the satisficing limit relaxation of G_1 to 1.7, to identify the same two common grid points with G_4. The satisficing limits of goals G_5, G_6, and G_7 are not relaxed as they already have common grid points with the critical goal, G_4.

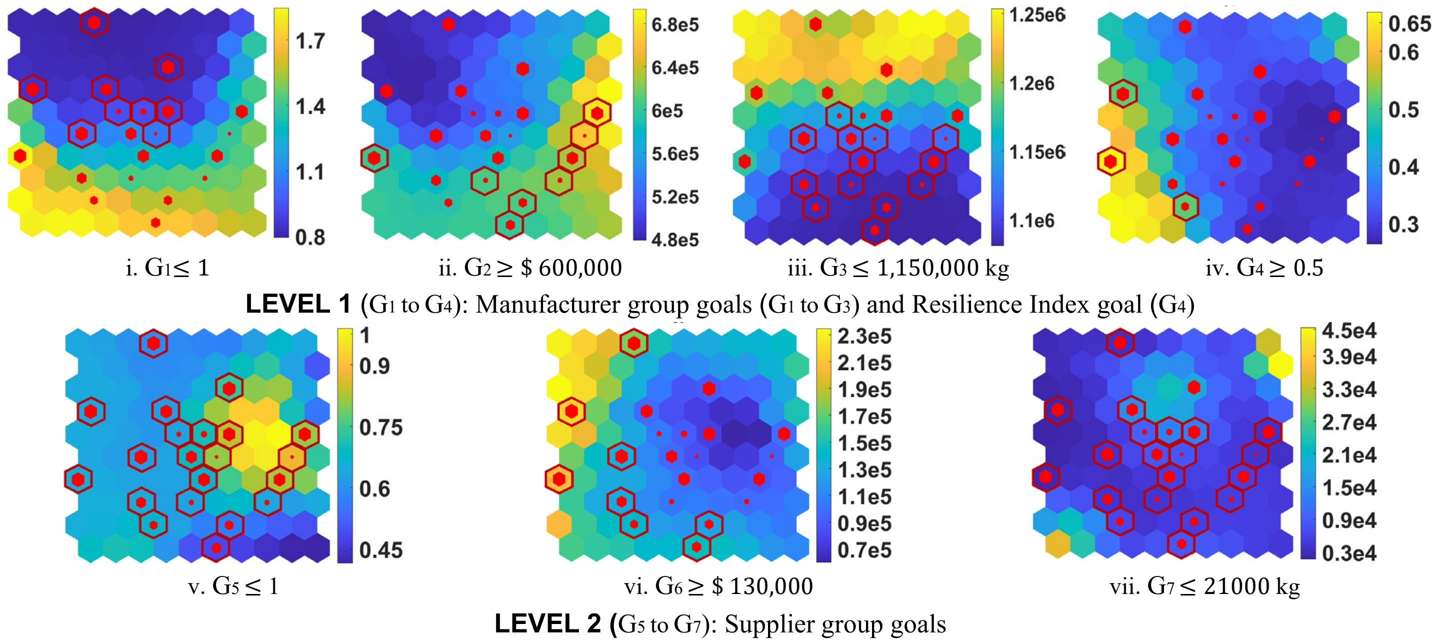

FIGURE 9: The iSOM plots for Goals (G_i) for the steel MSN problem. The grid points highlighted using red hexagons in the iSOM goals plots represent the initial satisficing solutions regions for goals.

With the relaxed satisficing limits, the updated satisfying regions for all the goals are identified and are depicted in Figure 10. With the updated satisficing regions, two points - 4 and 39, on the iSOM grid are identified as common satisficing regions for all the network and group goals across multiple levels. Five design scenarios: Scenarios 80, 86, 89, 97, and 104 are mapped to the two common iSOM grid points identified. These five scenarios represent '<u>five common satisficing solutions</u>' for the network, manufacturer group, and supplier group goals across multiple levels in the steel MSN problem. The goal values corresponding to the identified common satisficing solutions are listed in Table 3. In Table 3, the resilience index goal (G_4) values for network resilience for all 5 solutions are at or near the theoretical maximum value of 0.67. This indicates that the design solutions identified ensure higher resilience of the steel MSN.

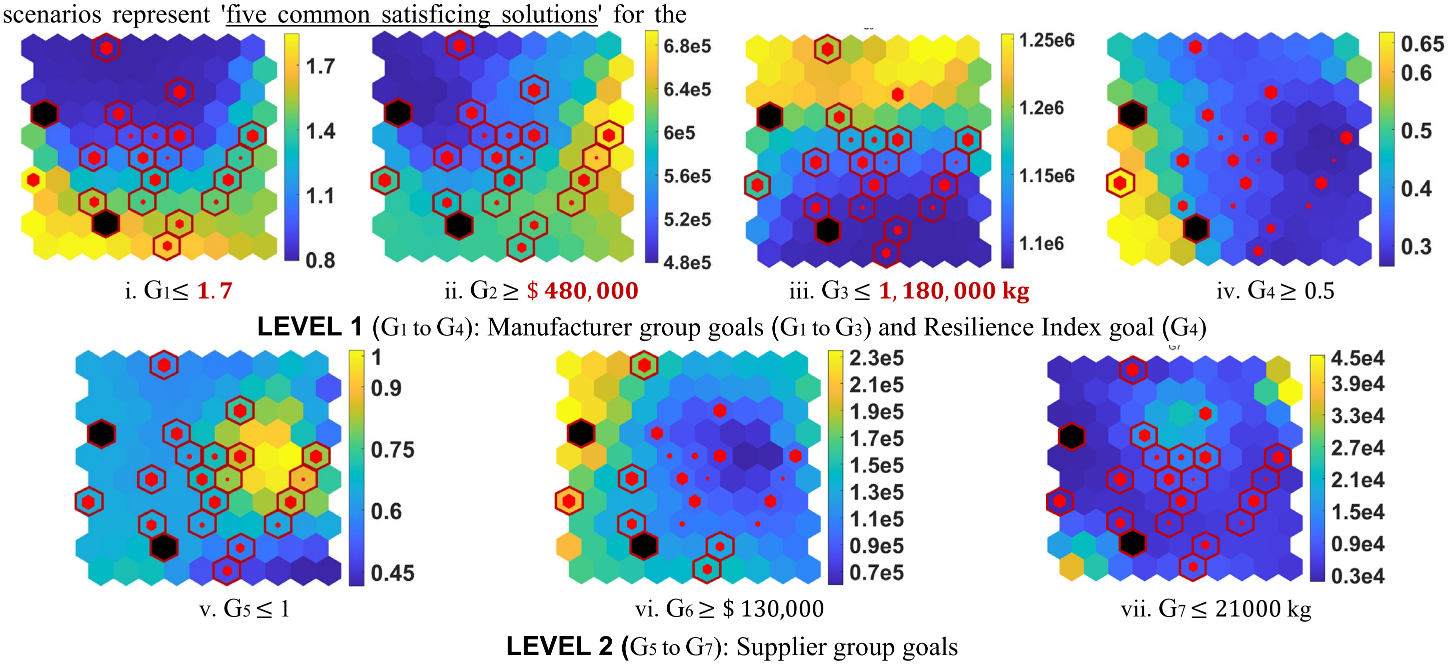

FIGURE 10: Satisficing solutions plots for goals after relaxation of satisficing limits. The black colored hexagons represent the common satisficing grid points for the network, manufacturer group, and supplier group goals across Levels 1 and 2.

TABLE 2. **Steel MSN network goal and manufacturer and supplier group goals values for the common satisficing solutions**

Design Scenario	W_1	W_2	W_3	W_4	W_5	W_6	W_7	G_1	G_2 ($)	G_3 (kg)	G_4	G_5	G_6 ($)	G_7 (kg)
80	0	0	0.5	0.5	0	1	0	1.56	526526.95	1087297.63	0.67	0.90	191138.26	6182.01
86	0	0	0.5	0.5	0.25	0.5	0.25	1.56	601364.72	1079865.97	0.67	0.65	208557.40	3785.62
89	0	0	0.5	0.5	0.2	0.6	0.2	1.56	601153.88	1080329.45	0.67	0.70	208483.04	3871.28
97	0.5	0	0	0.5	0.5	0	0.5	0.79	512925.98	1142601.11	0.50	0.65	166320.42	3428.44
104	0.5	0	0	0.5	0.33	0.34	0.33	0.79	500770.42	1140901.95	0.50	0.65	188898.42	3398.91

TABLE 3. **Design variable values for the manufacturer group decisions corresponding to common satisficing solutions**

Design Scenario	P_1 (tons)	P_2 (tons)	Q_{11}^1 (tons)	Q_{21}^1 (tons)	Q_{12}^1 (tons)	Q_{22}^1 (tons)	Q_1^1 (tons)	Q_1^2 (tons)	Q_2^1 (tons)	Q_2^2 (tons)	s_1^{1e} ($/ton)	s_1^{2e} ($/ton)	Y_{11}^1	Y_{11}^2	Y_{12}^1	Y_{12}^2	Y_{21}^1	Y_{21}^2	Y_{22}^1	Y_{22}^2
80	818.82	35.90	174.09	481.74	11.67	14.92	393.75	424.75	33.37	2.74	320.00	320.00	1	0	1	0	1	0	1	0
86	1.37	853.29	0.10	1.01	0.10	689.78	0.75	0.81	426.64	426.51	302.53	320.00	1	0	1	0	1	0	1	0
89	4.13	850.87	1.51	2.13	0.10	687.82	4.00	0.10	423.46	427.40	319.71	320.00	1	0	1	0	1	0	1	0
97	1.53	855.04	0.10	0.89	0.10	624.57	0.0	0.0	428.63	426.44	300.00	300.00	0	0	0	0	0	1	0	1
104	0.29	854.97	0.11	0.12	0.10	625.35	0.0	0.0	427.51	427.47	300.98	320.00	0	0	0	0	0	1	0	1

TABLE 4. **Design variable values for network decisions corresponding to common satisficing solutions**

Design Scenario	X_1	X_2	X_{11}	X_{12}	X_{21}	X_{22}	X_{11}^1	X_{12}^1	X_{21}^1	X_{22}^1
80	1	1	1	1	1	1	1	1	1	1
86	1	1	1	1	1	1	1	1	1	1
89	1	1	1	1	1	1	1	1	1	1
97	1	1	0	0	1	1	1	1	1	1
104	1	1	0	0	1	1	1	1	1	1

TABLE 5. **Design variable values for the supplier group decisions corresponding to common satisficing solutions**

Design Scenario	s_1^1 ($/ton)	s_1^2 ($/ton)	Y_{11}^{11}	Y_{11}^{12}	Y_{12}^{11}	Y_{12}^{12}	Y_{21}^{11}	Y_{21}^{12}	Y_{22}^{11}	Y_{22}^{12}
80	336.00	336.00	1	0	1	0	1	0	1	0
86	304.56	336.00	0	1	0	1	0	1	1	0
89	335.48	336.00	0	1	0	1	1	0	1	0
97	300.00	300.00	0	1	0	1	0	1	1	0
104	301.76	336.00	0	1	0	1	0	1	1	0

The manufacturer group, network, and supplier group design variable values corresponding to the common satisficing solutions identified are listed in Tables 4, 5, and 6, respectively. These design variable values determine the network structure (nodes and paths) and material flow (coal and steel slab) in the steel MSN.

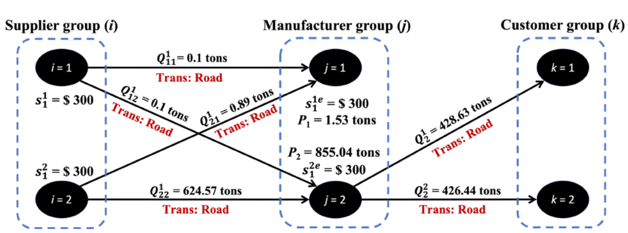

FIGURE 11: **The network structure and materials flow in the steel MSN corresponding to design variables for scenario 97 in Tables 3, 4, and 5. The black ovals represent the nodes in each group, and the arrows represent the paths connecting the nodes.**

For example, in Figure 11, we depict the steel MSN network structure, the material flow in the network, transportation modes employed, and other group-specific decisions corresponding to the design scenario 97. Therefore, using the CoDE-MR framework, the designer can model the network and group decisions across Levels 1 and 2 and their interactions within and across the levels using the c-cDSP construct. In the c-cDSP, the RI metric helps designers consider the connectivity and redundancy in the steel MSN as a network goal, thereby facilitating the identification of resilient steel MSN designs. By exercising the c-cDSP formulation for different multilevel design scenarios, the designer can generate the solution space for all network and group goals across the levels in the steel MSN problem. Using iSOM, the designer can visualize the solution spaces for all goals as separate 2D iSOM plots. Using these iSOM plots for the goals, the designer can simultaneously explore the multilevel network and group solution spaces, termed '*co-design exploration.*' Co-design exploration helps identify common satisficing solution regions (see Figure 10), where acceptable steel MSN resilience (RI value) and other group goals are realized simultaneously, helping manage conflicts. The design solutions identified using co-design exploration will ensure acceptable RI values while meeting the group goals, thereby realizing resilient steel MSN designs. The co-design exploration process is *'flexible'* as the designer defines 'modifiable goal satisficing limits' to help identify common satisficing solutions for all network and group goals. This further enhances the designer's freedom during early-stage design exploration and helps quickly identify a set of satisficing design solutions. Hence, using the CoDE-MR framework, the multilevel co-design exploration of steel MSN to ensure resilience is realized.

5. CLOSING REMARKS

MSNs are characterized by interrelated group decisions and network decisions across multiple levels of a decision hierarchy. The network decisions are directed toward realizing network goals, and group decisions are aimed at realizing group goals. The resilience of MSNs is a vital network goal that helps ensure satisfactory MSN functionality during disruptions. The connectivity and redundancy in the MSNs primarily determine the resilience. Given the relationship between network and group decisions, there can be potential conflicts between these decisions that impact the realization of the network resilience goal and group goals. Hence, it is vital to consider the relations among the multilevel group and network decisions and '*co-design the MSNs to ensure resilience.*' Co-design involves the simultaneous consideration of the network and group decisions. When the designer's focus during the early-stage design of MSNs is on quickly identifying satisfactory design solutions, the need is to facilitate the simultaneous exploration of the multilevel network and group solution spaces, termed '*co-design exploration of MSNs*.'

In this paper, we present the ***Co-D****esign* ***E****xploration of* ***M****SNs for* ***R****esilience* (CoDE-MR) framework to support the co-design of the network and groups to ensure MSN resilience. In the CoDE-MR framework, we integrate i) a combination of Preemptive and Archimedean formulations of the c-cDSP construct from DBD, ii) a graph-theory-based metric for network resilience - Resilience Index (RI), and iii) a machine learning-based visualization tool – iSOM. The c-cDSP construct allows designers to model the multilevel network and group decisions and their interactions. The Preemptive formulation of the c-cDSP allows consideration of decisions made hierarchically across multiple levels. The Archimedean formulation allows consideration of decisions made concurrently at the same level and multiple goals at a level. By combining the Preemptive and Archimedean formulations, designers can simultaneously consider decisions across multiple levels and multiple decisions and many conflicting goals at the same level. The RI metric helps designers consider the connectivity and redundancy in MSNs as a network goal, thereby facilitating the identification of resilient MSN designs. iSOM-based visualization helps designers i) visualize the multilevel network and group solutions spaces and ii) simultaneously explore these solutions spaces to identify a '*set of common satisficing solutions*' for the network and group goals across multiple levels. Therefore, using the CoDE-MR framework, the designer can i) model the multilevel network and group decisions and their relations in MSNs, ii) manage disruptions by identifying resilient MSN designs, considering the connectivity and redundancy in the MSN, and iii) visualize and carry out co-design exploration of the multilevel network and solution spaces, to identify resilient MSN design that also meets the group goals.

The CoDE-MR framework is tested for the above functionalities using the steel MSN problem. In the steel MSN problem, we consider network decisions and manufacturer group decisions at Level 1 and supplier group decisions at Level 2. The network decisions at Level 1 are directed towards maximizing the RI, and group decisions by the manufacturer and supplier groups are aimed at meeting the respective group goals. Using the CoDE-MR framework, co-design exploration of steel MSN to simultaneously realize the network resilience goal and group goals across multiple levels, is demonstrated. The conflicts among the related network and group decisions across multiple levels are managed by systematically exploring the solution space visualized using iSOM plots to identify common satisficing design solutions for the multilevel network and group goals. The use of generic constructs and tools imparts a generic nature to the framework, making it well-suited for co-designing multilevel systems to ensure resilience.

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APPENDIX A - Design variables, mathematical models for the goals, and level-specific information for the network and group decisions at Levels 1 and 2 of the c-cDSP for the steel MSN problem

What follows is an expansion of what is presented in Section 4.2. We list in A1, the design variables and their bounds corresponding to the network and group decisions at Levels 1 and 2 of the steel MSN. The mathematical models for the network and manufacturer group goals at Level 1 and supplier group goals at Level 2 are listed below in A2 and A3, respectively. In A4 and A5, we provide the information required specifically for the network and manufacturer group decisions at Level 1 and the supplier group decisions at Level 2, respectively.

A1. Design variables and their bounds in the c-cDSP for the steel MSN. (see Section 4.2.1)

i. Manufacturer group design variables (at Level 1)
   - Continuous (12):
     i. Production quantity at manufacturing facility 'j,' in tons (P_j)
        $$0.1 \le P_1 \le 1000$$
        $$0.1 \le P_2 \le 2000$$
     ii. Coal ($m = 1$) purchase quantities from suppliers in tons (Q_{ij}^m)
        $$0.1 \le Q_{ij}^m \le 3000$$

iii. Product supply quantities to customers in tons (Q_j^k)

For j = 1; $0.1 \leq Q_1^k \leq 1000$

For j = 2; $0.1 \leq Q_2^k \leq 2000$

iv. The estimated selling price of coal ($m = 1$) at supplier 'i' in \$ (s_m^{ie})

$$300 \leq s_m^{ie} \leq 320$$

- Binary – modeled as continuous (8):

i. Transportation mode selection (Y_{jk}^y)

$$0 \leq Y_{jk}^y \leq 1$$

ii. Network design variables (at Level 1)

- Binary – modeled as continuous (10):

i. Choice of manufacturing facility location to be opened (X_j)

$$0 \leq X_j \leq 1$$

ii. Material supply source selection (X_{ij}^m)

$$0 \leq X_{ij}^m \leq 1$$

iii. Customer choice for product distribution (X_{jk})

$$0 \leq X_{jk} \leq 1$$

iii. Supplier group design variables (at Level 2)

- Continuous (2):

i. The selling price of material 'm' at supplier 'i' (s_m^i)

$$300 \leq s_m^i \leq 336$$

- Binary -– modeled as continuous (8):

i. Transportation mode selection (Y_{ij}^{my})

$$0 \leq Y_{ij}^{my} \leq 1$$

A2. Models for the manufacturer group goals and network goal at Level 1 of the steel MSN. (see Section 4.2.1)

A. Manufacturer group goals

i. Minimize Average Service Level (ASL) to customers

$$G_1 = [\sum_{j=1}^{2}\sum_{k=1}^{2}\left\{\frac{\sum_{y=1}^{2}(\frac{D_{jk}^{y}}{Speed^{y}}+LT_{om}^{j}X_j)Y_{jk}^{y}}{LTk_{jk}^{e}}\right\}]/(\sum_{j=1}^{2}\sum_{k=1}^{2}X_j^k)$$

ii. Maximize manufacturer group profit (in \$)

$$G_2 = \sum_{j=1}^{2}[(Price\{\sum_{k=1}^{2}Q_j^kX_j^k\}) - (\{C_jX_j\} + \{P_j * PC_jX_j\} + \{\sum_{m=1}^{1}\sum_{i=1}^{2}s_m^{ie}\,Q_{ij}^mX_{ij}^m\} + \{\sum_{k=1}^{2}\sum_{y=1}^{2}Q_j^kD_{jk}^yT_{jk}^yY_{jk}^y\})]$$

iii. Minimize total GHG emission by the manufacturer group (in kgs of CO_2)

$$G_3 = \sum_{j=1}^{2}\left[\{P_jE_jX_j\} + \{\sum_{k=1}^{2}\sum_{y=1}^{2}Q_j^kD_{jk}^yE_{jk}^yY_{jk}^y\}\right]$$

B. Network goal

iv. Minimize Resilience Index

$$G_4 = (\sum_{i=1}^{2}\sum_{j=1}^{2}p_{ij} + \sum_{k=1}^{2}\sum_{j=1}^{2}X_j^k)/\{3(nodes-2)\}$$

where,

- Number of paths from supplier' i' to manufacturer' j', $p_{ij} = \min(1, \sum_{m=1}^{1}X_{ij}^m)$ for all values of $j = 1, 2$ and $i = 1, 2$
- $nodes$ – Maximum number of possible nodes in the network structure

For example, in the steel MSN problem, *nodes* = 6. This is the sum of the 2 supplier nodes, the 2 manufacturer nodes, and the 2 customer nodes.

A3. Models for the supplier group goals at Level 2 of the steel MSN. (see Section 4.2.1)

i. Minimize Average Service Level (ASL) to the manufacturer.

$$G_5 = \left[\sum_{i=1}^{2}\{\sum_{j=1}^{2}(\frac{1}{\sum m} * \sum_{m=1}^{1}\left(\frac{\sum_{y=1}^{2}(\frac{D_{ij}^{my}}{Speed^{y}}+LT_{os}^{i}X_j)Y_{ij}^{my}}{LT_{ij}^{me}}\right))\}\right] / (\sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{m=1}^{1}X_{ij}^m)$$

ii. Maximize total supplier group profit (in \$)

$$G_6 = \sum_{i=1}^{2}[\sum_{j=1}^{2}\{\sum_{m=1}^{1}(s_m^iQ_{ij}^mX_{ij}^m - (C_m^iQ_{ij}^mX_{ij}^m + \sum_{y=1}^{2}D_{ij}^{my}\,Q_{ij}^m\,T_{ij}^{my}Y_{ij}^{my}))\}]$$

iii. Minimize GHG emissions (in kgs of CO_2)

$$G_7 = \{\sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{m=1}^{1}\sum_{y=1}^{2}D_{ij}^{my}Q_{ij}^m\,E_{ij}^{my}Y_{ij}^{my}$$

A4. Information required for the network and manufacturer group decisions at Level 1 of the steel MSN. (see Section 4.2.1)

For network decisions:

- *Manufacturer group (j) information*: Set of manufacturing facility locations (j = 1, 2)
- *Supplier group (i) Information*: Set of suppliers (i = 1, 2)
- *Customer group (k) information*: Set of customers (k = 1, 2)

For manufacturer group decisions:

- *Manufacturer group (j) information*: set of manufacturing facility locations (j = 1, 2), Setup cost of at location 'j' (C_j), production cost (PC_j) in \$ per ton at location 'j', order processing lead times at location 'j' in hours (LT_{om}^j), raw material (m) requirement in tons per ton of steel produced $\{A_m\}$ (coal, m = 1), transportation information – (modes {y = *1, 2*}, speed in km/hr $\{Speed^y\}$, distance to customers in km $\{D_{jk}^y\}$, transportation costs in \$ per ton per km using mode 'y' $\{T_{jk}^y\}$, greenhouse gas {GHG} emission in kgs of CO_2 per ton transported per km $\{E_{jk}^y\}$), GHG emission in kgs of CO_2 per ton of steel product produced (E_j), product price per ton (*Price*), and demand estimate at customer 'k' (D_k^e).
- *Network information*: choice of manufacturing facility location to be opened (X_j), material supply source selection (X_{ij}^m), and customer choice for product distribution (X_{jk}).
- *Customer group (k) information*: set of customers (k = 1, 2) and expected lead time in hours (LTk_{jk}^e) from manufacturer facility' j.'

A5. Information required for supplier group decisions at Level 2 of the steel MSN. (see Section 4.2.1)

- *Manufacturer group (j) information*: actual order quantity of material 'm' (Q_{ij}^m) and expected lead time for material 'm' in hours (LT_{ij}^{me}) from supplier 'i.'

- *Network information*: choice of manufacturing facility location to be opened (X_j) and material supply source selection (X_{ij}^m).
- *Supplier group (i) information*: set of suppliers (i = 1, 2), materials supplied {m = 1 (coal)}, material cost of material 'm' in $ per ton, (C_m^i), transportation information – (modes {y = *1, 2*}, speed in km/hr {$Speed^y$}, distance to customers in km {D_{ij}^{my}}, transportation costs in $ per ton per km {T_{ij}^{my}}, GHG emission in kgs of CO_2 per ton transported per km {E_{ij}^{my}}), and order processing lead times at supplier 'i' in hours (LT_{os}^i).