Weighted Distribution Sociomatrix for Co-Exploring Decision-Making Process

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Weighted Distribution Sociomatrix for Co-Exploring Decision-Making Process

Christian Quintero

Abstract— **This paper purposes a multidisciplinary co-exploring decision-making problem for integrating diverse information. To analyze flow messages in a complex social system that allows consensus problems from diverse disciplines and perspectives. Consequently, transform heterogeneous information into a digraph for representing directional relations, this approach integrates diverse data using a centrality weighted degree of graph theory. Indeed, the main contribution of this paper is a digraph construction based on Interpretive Structural Modelling (ISM) and cross-impact matrix multiplication (MICMAC) that includes a centrality weighted degree results from a collective sense-making and common ground. The co-exploring decision-making from a generative sociomatrix is defined from the individual-perspective to group-decision. Moreover, the sociomatrix is calculated based on centrality weighted degree. Data collection from a participatory design approach includes a person-user and four disciplines with their voice of thoughts and ideas. The results present that the approach proposed helping to construct a multidisciplinary collective sense-making. The centrality weighted degree interpretation based on ISM, and MICMAC analysis effectively integrates heterogeneous information with digraph and facilitates the co-exploring decision-making problem.**

Index Terms— **Collaboration, complex systems, information fusion, multidisciplinary decision-making, reachability analysis, centrality weighted degree.**

I. Introduction

MULTIDISCIPLINARY research experiences involvement in research processes has positive outcomes as there are views on the most successful community solution. For instance, the research evaluates the difficulty of opening jars with screw tops through focus groups involving people with reduced mobility in their hands. The prototypes were therefore planned to make this task easier using participatory design. Similarly, the ATOLL tool presented possible solutions in a tridimensional environment, allowing research to be used as a tool to consider and dialogue the advantages and disadvantages of the product concept [1]. Another research involving a multidisciplinary group from education, therapeutics, and computer science disciplines developed interface design usability criteria to minimize distress in using and tracking learning in autism-infants [2].

Other works have implemented the probing process with participatory design. For example, in Ghana, the co-explore improves the effects of socio-cultural women dynamics. They have participated in the communication process to gain empathy [3]. The process builds an atmosphere that will allow key stakeholders to find solutions for emerging problems. Other studies with caregivers as participants are involved in the design process that allowed information needs through open participation [4]. Therefore, the authors indicate that probes have benefits as research tools for understanding when designing with users in African communities. The socio-cultural context of participants should be considered in designing the probes [3], [4].

The study of complex systems should extract common scientific problems and the common deduction knowledge from these problems. It is even considered that the appearance and development of complexity science is the key for all sciences to move beyond reductionism to holism, that is, to re-integrate or re-unify separate disciplines [5].

From a complex social system, the data can be linked in a two-way matrix where the rows and columns refer to the actors making up the pairs as a sociomatrix [6]. The relationship between the socio-dynamic effect can be represented by complex network data from a set of actors. Substantial concerns and theories that motivate a specific network study usually determine which variables to measure and often which techniques are most appropriate for their measurement [7].

Complex representational researchers and practitioners such as Systemic Design [8] and DesignX [9] are oriented to complement design methods for complex social and service systems based on Designs 3.0 and 4.0 [10], the collaboration between decision-makers, experts, and stakeholders is becoming a prerequisite for facilitating agreements and alleviating risks of foresight and uncertainty in the implementation of complex organizational problems. Systemic design finds ways to balance trade-offs between complex representational validity, called ease-of-view. For example, the Leverage Analysis Method for Location of Points of Influence in Systemic Design Decisions, which carried out a case study of the innovation system in Canada. This work applied techniques based on graph theory and system dynamics. These techniques make it easier to take advantage of large-scale data in systemic design [11], [12].

Similarity, In the same way, Norman and Stappers [9] described various problems of DesignX related to complex societal systems in different categories, one of them, the social, political, and economic framework of complex socio-technical systems reflecting the fundamental characteristics of socio-technical systems that require most solutions to involve complex trade-offs. For example, multiple disciplines and perspectives can centrally influence design; each discipline brings different forms of challenge based on expertise and experience, emphasizing different aspects of the problem.

The methods and processes relating to complex systems and participatory design are oriented to collective decision-making. The literature presents research based on heterogeneous information analysis. In such cases, a collective of decision-makers is involved in the decision-making process, which is usually assessed in diverse linguistic scales because decision-makers provide distinct knowledge and background. The proposed computational model based on extended linguistic hierarchies can provide interpretable linguistic results to decision-makers [13]. Another work is the Group Decision Making (GDM) method for integrating heterogeneous data into normalized decision-making matrices with a weighted average power operator. Consensus processes and feedback mechanism with the iterative computational process to adjust the individual decision matrix [14], but the authors indicate that dynamic GDM is a potential work that will be implemented.

This paper implements Interpretive structural modelling (ISM) [15] and cross-impact matrix multiplication (MICMAC) [16] approaches that help the model structure analysis of the cycles found in graphs and testing system dynamics models [17]. Recall that systems dynamics models use rate and equation modelling drawn from real-world data. The nature of the phenomena modeled can be challenging to measure and integrate these real-world measures into a model. The ISM foundations can be found in decision support systems, product design, and decision-making in various applications. ISM is an interactive process that directly related factors are structured into a comprehensive systematic model.

The conceptual and analytical details of the ISM integrated with the MICMAC process are presented by many authors. Khan and Haleem [18] discussed the emerging organizational paradigm called smart organization had been identified as a strong driving power from culture, technology support, leadership, top management support, and team working into smart companies. Sharma, Grover, and Sharma [19] used ISM and MICMAC to recognize the barriers that affect the utilization of quality tools and techniques in manufacturing organizations. In the same line, Dawood and Underwood [20] identified variables of small and medium enterprises to assist decision-makers in setting successful and sufficient strategies and policies that clarify the ambiguity surrounding the planning process. Karadayi-Usta [21] discussed the adoption challenges in industry 4.0 and described various causes of implementation challenges and barriers from MICMAC analysis results. Rade, Pharande, and Saini [22] identified factors responsible for heat transfer in the recovery of heat and parameters that requires more attention.

The decision-making process requires identifying various variables as messages categorizing a problem. It includes a structured approach of a set of variables identifying relationships among specific concepts or meanings which define a problem. The contribution of this paper is a new stage to be included in an ISM method that establishes a group of elements from centrality weighted degree relation as dynamic collective dialogue space. The proposal allows increases communication action between disciplines and person-user oriented to the collective decision-making process. The complex responsive process of connecting problems presupposes that engagement in the design process allows for consensus and a sense-making process.

The rest of this paper is structured as follows. Section II describes a problem characterization and abstraction of a complex socio-technical system, participatory design, and decision-making process. Also, I describe an empirical case study implemented. Section III definitions and notations for mathematical foundations for graph theory require interpreting the communications relations. Section IV describes which messages as nodes in the network should be targeted to the fusion and weighted distribution of all or most nodes in the network. Section V presents concepts and processes of the ISM integrated with MICMAC for analyzing the relationships among specific elements that define a problem. Section VI presents the analysis for a practical case study that includes interpretations of the co-exploring process. Section VII comparison analysis was performed to validate the effectiveness of the proposed method, and the last section shows the conclusions and final remarks.

II. Problem Characterization and Abstraction

This section describes a complex socio-technical system with multiple disciplines and perspectives to co-explore the real problem with collective decision-making. The presence of multiple disciplines and perspectives can centrally influence design; each discipline brings different forms of face-up based on expertise and experience, emphasizing different aspects of the problem. Particularly, each discipline has a technical language with specific terms that are different, but different terms are often used with the same meanings or the opposite way, the same term with different meanings [9]. These differences can impact the functioning of the process because they can be disrupted collaboration. Therefore, it can be considered a communication action problem when transferring a message between disciplines.

The co-exploring is based on the probing method [23], [24] inside of a pre-design stage into a co-design process [25], allows exploring user participation by self-reporting, perceptions, and exploratory mindsets. Besides, the multidisciplinary group collaboration involves people in human-centered design dialogues [26]. These dialogues are keys to developing the understanding of the users, sense-making of the design group. Therefore, the problem of communication action extends because a group can understand multiple messages.

When transferring a message, the embedded representation system can interpret the communication action resulting in a directed graph for the complex system for a given contextual relationship amongst a set of elements. The potential of graph theory deals with interpreting a complex social system in a directed graph a given contextual relationship in a set of messages [11]. This paper represents graph theory to help the reader understand the ISM process based on weighted degree centrality relations. The technical implementation details have been well-defined in section III, and the main goal is to map their utility to interpretation in a multidisciplinary co-exploring design.

The decision-making process identifies various variables as messages categorizing a problem. It includes a structured approach of a set of variables identifying relationships among specific concepts or meanings which define a problem. Interpretive Structural Modelling (ISM) [27] is a decision-making tool that helps determine complex relationships among multiple ideas or concepts. Also, it finds out the order and influence by identifying the relationships among the elements [28]. ISM analyzed unclear mindsets of systems into visible, well-defined models useful for decision-making problems. However, the ISM has not provided a dialogue space among the participants, and neither has it allowed to obtain a collective sense.

A. Case study

The multidisciplinary co-exploring design was implemented in a case study based on enhancing the capabilities of the person with a motor impairment—the exploring capability-sensitive value [29] for professional labor as a productive activity. Multiple disciplines integrated the case study with roles that deeply understand medicine, psychology, design, and engineering. Also included, the person-user with motor impairment involves in the design process and a facilitator of a participatory process. Correspondingly, capability patterns collect a pivotal characteristic to establish criteria or requirements for the problem-solution design. Each discipline and role are described the following:

1) Medicine discipline

A medical doctor with physical medicine and rehabilitation experience supported a medical diagnosis of physical capabilities and motor functions of the person-user. Also, advise, evaluate and supervise fabrication and adaptation of design orthoses, prostheses, and other assistive technologies.

2) Psychology discipline

A social psychologist is concerned with how the person-user thinks, feels, and behaves and how they are affected by social influences. The role evaluates the emotional aspects of the behaviors and beliefs of the person-user.

3) Engineering discipline

Computer Engineering experts on Human-Computer Interaction (HCI) role supports the technology usability and definition of protocols that oriented the activity-tasks of the person-user.

4) Design discipline

An Industrial design and ergonomic expert, the role leads influence human factors that contribute to product design focused on disability patterns. A facilitator is a design researcher with an emphasis on participatory design and accessibility technology. The role helps to design toolkits that stimulate dialogues, opinions, and interpret collective decisions for sense-making [10], [24], [30].

5) Classmate

The participant is a friend and shared classes in Multimedia Engineering Program. The role allows complementing different factors from weakness and strongness about skills in Multimedia Engineering of the person-user.

6) Person-user

The participant with motor impairment is an expert from their disability experience and diffuse designer as a Multimedia Engineering student. The participant has two roles; the first role contributes with an active voice about disability life experience, motivation, and needs. The second role in multimedia engineering skills implements designs and developments in two- and three-dimensional environments.

For an extended description of a participant with motor impairment, the contextualization based on a work accident at the age of 23 was diagnosed with tetraplegic to spinal cord injury. The injury presented a partial movement of the upper limbs, absence of mobility in lower limbs, and absence of sensitivity. Furthermore, the participant preserved their shoulder and elbow active mobility, but his fingers have not an autonomous movement in the current time.

III. Definitions and Notations

In the section, some basic definitions and notations below will be used throughout this paper.

Relational data is usually presented in two-way matrices called sociomatrices. The sociomatrix has two dimensions indexed by the rows that send a message by actor and the columns receiving a message by an actor. Thus, in a one-mode network, the sociomatrix will be square [6].

For example, a single relation expressed on one set of g actors in $N = \{n_1, n_2, \dots, n_g\}$ let R refer to this single-valued, directional relation. In entry $\{i, j\}$ for a sociomatrix indicates that $n_i \rightarrow n_j$ on relation R. Thus, the relation R is defined by X as the associated sociomatrix [7]. This sociomatrix has a value of the tie from n_i to n_j is assigned to element (i, j)th of X defined as X_{ij} the value of the tie from n_i to n_j on relation R

where i and j are $(i \neq j)$ range over all integers from 1 to g, let us assume self-choice [7] sociomatrix diagonal identity $\{X_{ii}\}$ the values are 1.

The information in a graph may be expressed in a variety of ways in matrix form. In this case, the incidence matrix is useful to be represented a single non-directional relation (graph) and then generalize to matrices for directional relations (digraphs) [7].

A digraph G consists of a set of nodes, $N = \{n_1, n_2, \dots, n_g\}$, and a set of lines, $L = \{l_1, l_2, \dots, l_h\}$ between pairs of nodes. There are g nodes and h lines. In a digraph, each line is an unordered pair of distinct nodes, $l_k = (n_i, n_j)$.

In graph theory, the subgraph in the graph is defined by a set of connected nodes. A subgraph in which there is a path between all the node pairs in the subgraph can be reached. If there is only one subgraph in the graph, the graph will be connected, but more than one subgraph will be disconnected [7].

Let us describe and explain the properties used to analyze the connectivity of the graphs, to define the density of a digraph is equal to the proportion of lines present in the network. It is calculated as the number of lines, L, divided by the possible number of lines. Since a line is an ordered pair of nodes, there are $g(g-1)$ possible lines. The density denoted by Δ, and defined as [7]:

$$\Delta = \frac{L}{g(g-1)} \quad (1)$$

The density of a graph goes from a minimum of 0, if there are no lines present $(L = 0)$ to a maximum of 1, if all possible lines are present.

The degree of a node in the sociomatrix is the number of links (lines) incident on the node, denoted by k. In the sociomatrix X with elements $\{X_{ij}\}$ the degrees of the nodes are equal to the row sums or column sums. The ith row or column corresponds to total gives the degree of node n_i is calculated by using (4). A directed graph can get two measures that depend on the in-degree (the number of receiving messages) and the out-degree (the number of sending messages). The number of rows i is incident from node n_i and is equal to the outdegree of node n_i is calculated by using (2). Similarly, the number of columns i is equal to the in-degree of a node n_i is calculated by using (3). Thus, the row totals of X are equal to the nodal outdegrees, and the column totals of X are equal to the nodal indegrees [7], [31].

$$k_i^{out} = \sum_{j=1}^{g} X_{ji} \quad (2)$$

$$k_i^{in} = \sum_{j=1}^{g} X_{ij} \quad (3)$$

The influence of a node can be quantified by the number of ties from a node k^{out} while the number of ties that are directed towards a node k^{in} is an indicator of notoriety. Moreover, since not all ties are not reciprocated, thus k^{out} can be different to k^{in}.

$$k_i = k_i^{in} + k_i^{out} \quad (4)$$

Additionally, the degree has been extended by weights when analyzing weighted networks [32] and labeled node strength. This notation has been defined as:

$$s_i^{in} = \sum_{j=1}^{g} w_{ij} \quad (5)$$

$$s_i^{out} = \sum_{j=1}^{g} w_{ji} \quad (6)$$

$$s_i = s_i^{in} + s_i^{out} \quad (7)$$

IV. FUSION AND WEIGHTED DISTRIBUTION OF DIGRAPH

In this section, I want to consider the probability of a communication action between actors involving sending or receiving messages. I assume that lines have different weights and that communications travel along the path.

Various elements that set up the system maintain a degree of dependence from one another. Thus, when the dependencies among the elements become important. In such a system, the fusion of a set of elements into an emerging collective element does not fundamentally alter the behavior of the system, but reduces the level of complexity because it can arise the degree of dependence among elements of the full system. The fusion of elements constructs a collective sense-making system between actors. In addition, each actor can send or receive multiple messages and become increases the complexity of the system.

The method focuses on which messages as nodes in the network should be targeted to ensure that the data spread to all or most nodes in the network. Thus, the nodes fusion and weighted distribution can be calculated using the following steps:

Step 1: Let a digraph $G = (N, L, S)$ consists of a set of nodes, $N = \{n_1, n_2, \dots, n_g\}$, and a set of lines, $L = \{l_1, l_2, \dots, l_h\}$ with a set of weighted values between pairs of nodes.

Step 2: Select a subgraph G_∂ based on s_i^{out} path with a high weighted outdegree. There are g_∂ nodes and h_∂ lines.

Step 3: From a digraph G_∂ for each line, the weighted distribution [33], [34] $l_k = (n_i, n_j)$ is calculated by coefficient of relation μ_f, and defined as:

$$\mu_f = \frac{\sum_{k=1}^{h_\partial} s_k}{h_\partial} \quad (8)$$

Step 3: For each line l_k assigned the fusion node $l_k = (n_f, n_j)$, and $l_k = (n_i, n_f)$. If there are lines $l_k = (n_f, n_f)$that indicated that no relation itself then must be removed l_k. Also, if there are lines $l_k = (n_i, n_j)$ duplicate, the relation is calculated by the sum of l_k weighted values above the total of line duplicates.

Step 4: The weighted relation is calculated of each weighted directional relation value. In entry $\{f, j\}$ for a subgraph indicates that $n_f \rightarrow n_j$ on relation R_f, and defined as:

$$R_f = \frac{s_k + \mu_f}{2} \quad (9)$$

An example of a G graph in a social network would be a relation such as communicates with, where all g nodes communicated with all other nodes. Let me illustrate a random weighted network adapted from Newman [35] with a set of nodes, $N = 10$, and a set of lines, $L = 12$ between pairs of nodes. In a graph each line is an unordered pair of distinct nodes, $l_k = (n_i, n_j)$. The weighted outdegree centrality represents a transmitter system that involves a set of messages that measures expansiveness (see Fig. 1a).

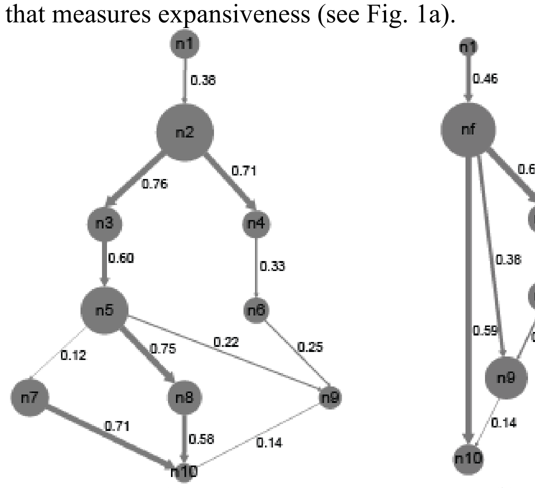

Fig. 1. (a) The G graph represents a weighted network. (b) the result G' graph from fusion and weighted distribution relation.

The subgraph G_∂, a set of nodes $N_f = \{n_2, n_3, n_5, n_7, n_8\}$ have a high common ground between each other. The complete graph in a social network would be a relation such as communicates with, where all g messages communicated with all other messages.

The weighted distribution is calculated from G_∂ of the coefficient of relation $\mu_f = 0{,}54$ is calculated by using (8), and each recorded weighted relation is assigned the fusion node. After that, removes lines $l_k = (n_f, n_f), L = 4$ that indicated that avoid the relation, and duplicates relations were calculated for lines $n_f \rightarrow n_{10}$ twice. Finally, the G' graph is calculated by using (9) from each weighted directional relation that $n_f \rightarrow n_j$ on relation R_f (see Fig. 1b).

The method is compared between G and G', based on the analysis of the density of each digraph that represents the connectivity among nodes. For G is equal to $\Delta = 0{,}133$, and G' is equal to $\Delta = 0{,}233$ is calculated by using (1), the results infer that the connectivity nodes from G' increases the communication with all other nodes concerning G.

V. ISM AND MICMAC PROCESS TO ANALYSIS

ISM enables individuals or groups to prepare a map of the complex relationships between the various elements involved in a complex system. The basic idea is involved practical experts and knowledge in decomposing a complicated system into several sub-systems as elements and construct a multilevel structural model. ISM is used to represent a fundamental understanding of complex situations and set together address of action for decision-making to problem-solving. ISM can be used for finding and analyzing the relationships among specific factors, which define a problem. The various steps involved in the ISM integrated with the MICMAC process are as follows [19], [22], [36] (see Fig. 2):

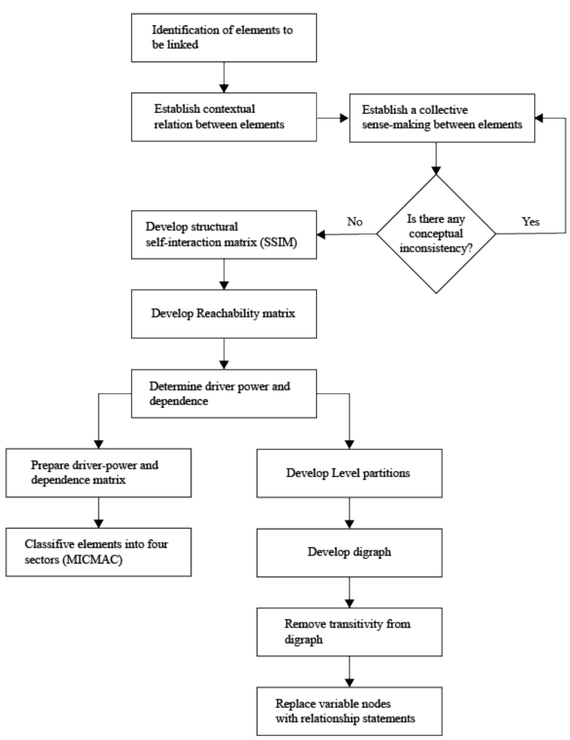

Fig. 2. Flow diagram for process sequence of ISM model (adapted from [19])

Identification of elements to be linked: the system elements are identified, relevant to the outlined problem, and identified with collecting data as a group by opinions and ideas from different expert domains.

Establish contextual relation between elements: from the elements identified, a contextual relationship among each element to whom pairs of elements would be examined.

Establish a collective sense-making between elements: this step is included as a contribution of this paper, establishing a group of elements from centrality weighted degree relation. The group collaboration involves people in human-centered design dialogues. These dialogues are keys to developing the understanding of the problem and construct a sense-making among the group. This step can have several iterations because the social process is non-linear, and the contributions of each participant must be shared and reflected. In section IV, the contribution was described in deep.

Develop structural self-interaction matrix (SSIM): the matrix represents the perception of an element to another one directed relationship. Considering the contextual relationship in each element based on the existence of a relation between two elements $n_i \rightarrow n_j$ associated direction on relation R. From each element, four symbols represent the type of relationship between the two elements under consideration. The symbols are:

V: Factor i will help achieve factor j.
A: Factor i will be achieved by factor j.
X: Factor i and j will help achieve each other.
O: Factor i and j are unrelated.

Develop a reachability matrix: From the SSIM, the transitivity of the contextual relation is a binary matrix that reflects the directed relationships between elements defined. From substituting of V, A, X, O relationship by 1 and 0 as each relation (i, j). The rules for the substitution are:

Rule 1: If is V, thus the relation (i, j) becomes 1, and (j, i) becomes 0.

Rule 2: If is A, thus the relation (i, j) becomes 0, and (j, i) becomes 1.

Rule 3: If is X, thus the relation (i, j) becomes 1, and (j, i) becomes 1.

Rule 4: If is O, thus the relation (i, j) becomes 0, and (j, i) becomes 0.

Determine driver power and dependence: From the reachability matrix, the calculation of driver power and dependence for each element is based on the sum of elements in each row for driver power and the sum of elements in each column for dependence, after determining the power of the driver and the dependence, the information branches in two ways—first, the representation for a digraph, and second the classification elements by MICMAC sectors.

Develop digraph: The digraph is a representation in various levels that examined the influences of elements. The elements identified in the level partitions stage through drive power and dependence of elements. To arrange the levels, Determine the reachability and antecedent sets for all the elements. The elements in the top level of the hierarchy will not reach any elements above their level. The transitive links are removed based on the relationships given in the reachability matrix. The resultant digraph is converted into an ISM by replacing nodes with statements.

Develop MICMAC: MICMAC is known as cross-impact matrix multiplication applied to analyze the driving power and the dependence of the variables [16]. MICMAC helps to classify elements into sectors with the calculation of driver and dependence power for each element. The result can be shown in the matrix of the driver-dependence diagram and categorizes into the following four sectors [16]:

1) Sector I: weak driver and dependence power that the significant elements relatively disconnected from the system, which promptly detached with few links, is called autonomous variables.

2) Sector II: weak driver and strongly dependent variables that elements are resultant of the system, with significantly by other elements, is called dependent variables.

3) Sector III: strong driver and strongly dependent variables that elements are naturally unstable because any action made by these variables will affect others and feedback effect on themselves, is called linkage variables.

4) Sector IV: strong driver and weak dependent variables that condition the rest of the system is called independent variables.

VI. Practical Case Study

Initial co-exploration seeks to enhance the capabilities of the person with disabilities to tune to the problem outline in the multidisciplinary design group. This issue should improve social integration through professional labor as a productive activity, and capacity patterns should be linked to a specific interest domain user.

In this practical case study involves multidisciplinary practical experts and knowledge to decompose a complex system into several sub-systems as elements and construct a multilevel structural model. The ISM and MICMAC analysis process is implemented to represent a fundamental understanding of complex situations and to work together to address decision-making to problem-solving.

A. Identification of elements to be linked.

The workshop designed by two activities an individual gazed at and a collective shared data. First, previously each participant gazed a video recording based on the real-world situation that involves a professional assignment. For an individual activity, they have to take notes and set a time for actions, postures, or behaviors that represent criteria problems. In the second activity, the design group met to share the viewpoints, which describes and categorizes the maximum four criteria by a data collection tool called the knowledge matrix. After each matrix was shared among participants and they could write, highlight, or discuss the ideas of others. Indeed, the communication action as a no-verbal dialogue between participants attempts to identify relevant cognitive and behavioral aspects of the person-user in the activity (see Fig. 3).

Fig. 3. Meeting of non-verbal dialogues of the design group from the knowledge matrix toolkit.

The design group defined elements from each specific discipline domain and practical experiences. Table I presents 23 criteria, such as a result of the workshop. However, the psychology discipline participant could not be in collective activity, but problem criteria were included in identifying elements list.

TABLE I
IDENTIFICATION OF ELEMENTS TO BE LINKED

SN	Criteria (Translated)	Criteria (Spanish as native language)	Domain
n1	Physical space interaction	Interacción con el espacio físico	Engineering
n2	Conceptual activity interaction	Interacción conceptual con la actividad	Engineering
n3	Environment	Entorno	Classmate
n4	Rationality	Racionalidad	Facilitator
n5	Interaction activity-productive relationship	Interacción relación productiva por objetivo de la actividad	Design
n6	Work desk	Mesa de trabajo	Medicine
n7	Position of person-user	Posición de persona-usuario	Medicine
n8	Work items	Elementos de trabajo	Medicine
n9	The computer as a work tool	Ordenador como herramienta de trabajo	Person-user
n10	Work area	Sitio de trabajo	Person-user
n11	User interface interaction	Interacción con la interfaz de usuario	Engineering
n12	Comfort and displacement	Comodidad y desplazamiento	Classmate
n13	Design process	Proceso de diseño	Facilitator
n14	Operativity	Operatividad	Facilitator
n15	Experience - learning - performance	Desempeño (aprendizaje, experiencia, precisión, prontitud, satisfacción)	Design
n16	Control effort operating devices	Conjunto operante mandos en esfuerzo de la actividad	Design
n17	Intrinsic and extrinsic motivation	Motivación retos individuales y social en la actividad	Design
n18	Software used	Software utilizado	Person-user
n19	Recording the activity	Grabación de la actividad	Person-user
n20	Language	Lenguaje	Psychology
n21	Sensory motor functioning	Funcionamiento sensorial motor	Psychology
n22	Cognitive functioning	Funcionamiento cognoscitivo	Psychology
n23	Insight and judgment	Insigh y juicio	Psychology

B. Establish contextual relations between elements.

The knowledge matrix collected 23 criteria, and a collaboration group defined each criterion. Likewise, an individual activity made a contextual relation from a knowledge matrix tool between elements as 0,0 (no relation) or 1,0 (relation) to build a sociomatrix. As a result, seven sociomatrices were compiled as one matrix data. After that, the values were normalized to establish weighted relation. This weighted value meant that all participants recognized that these criteria refer to the same topic or not.

C. Establish a collective sense-making between elements.

The complex system of relating the assumption that identifies various elements as messages categorizing a problem. The digraph G representation in a social network, with a set of elements of $N = 23$, and a set of lines of $L = 225$ between pairs of nodes. In a digraph, each line is an unordered pair of distinct nodes associate with a weighted relation. The size node illustrates weighted outdegree centrality is calculated by using (6) and representing a transmitter system that involves a set of messages that measure expansiveness (see Fig. 4).

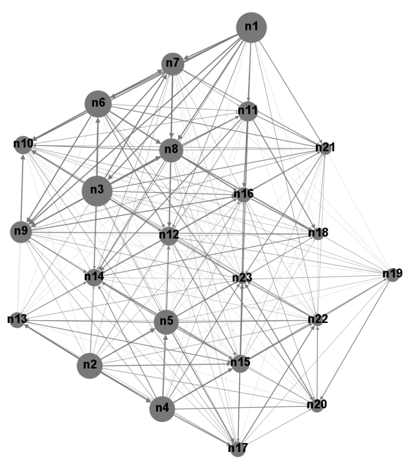

Fig. 4. The digraph G representation of complex system into a social network from the design group interpretations.

Based on high weighted outdegree (see Table II), the subgraph G_∂, a set of nodes $N_f = \{n_1, n_2, n_3, n_4, n_5, n_6, n_7, n_8, n_9, n_{10}, n_{11}, n_{12}\}$ with a set of lines of $L = 59$ between pairs of nodes. The second collective workshop facilities a dialogue among participants through unifying terms, definitions, and categories. Each participant argued and consensus the relationships between categories allow unifying and fusion elements with three new criteria: workplace, cognitive process, and executing process.

TABLE III
WEIGHTED DEGREE CENTRALITY

SN	Weighted indegree	Weighted outdegree	Weighted Degree
n1	0	10,55	10,55
n2	0	8,07	8,07
n3	1,29	10,58	11,87
n4	1	7,99	8,99
n5	2,57	7,54	10,11
n6	2,14	8,69	10,83
n7	3,57	6,57	10,14
n8	4,28	7,13	11,41
n9	5,86	5,99	11,85
n10	5,99	4,15	10,14
n11	4,41	5,03	9,44
n12	5,99	4,43	10,42
n13	3,99	2,86	6,85
n14	7,42	3,72	11,14
n15	6,13	4,01	10,14
n16	8	2,58	10,58
n17	5,34	2,58	7,92
n18	6,3	0,99	7,29
n19	3,29	1,85	5,14
n20	4,89	1,57	6,46
n21	7,7	1	8,7
n22	7,71	0,71	8,42
n23	10,72	0	10,72

Iterations required redefinition through consolidated terms and different fusion result to workplace n_{24} criteria following the fusion relations: $n_{24} \rightarrow (n_1, n_3, n_{10})$, based on $n_3 \rightarrow (n_6, n_8)$, and $(n_6, n_8) \rightarrow n_7$ that fusion requires redefinition through consolidated terms and redefinition. Besides, the design group making-decision argued that elements (n_2, n_4, n_5) have common ground attributes, but it did not possible to determine a complete relationship between them. Therefore, two collective categories emerged cognitive process n_{25} and executing process n_{26} which requires to be defined specifics criteria (see Table III).

TABLE IIII
CO-EXPLORING ELEMENTS TO BE LINKED

SN	Criteria (Translated)	Criteria (Spanish as native language)	Domain
n24	Workplace	Puesto de trabajo	Design group
n25	Cognitive process	Proceso cognitivo	Design group
n26	Executing process	Proceso ejecutor	Design group

The weighted distribution is calculated from each fusion criterion based on the coefficient of relation. Thus, for n_{24} is equivalent to $\mu_f = 0{,}51$, and (n_{25}, n_{26}) is equivalent to $\mu_f = 0{,}53$ is calculated by using (8), and each weighted relation is recorded. After that, removes lines $l_k = (n_f, n_f)\ L = 18$ that indicated that avoid the relation and duplicates relations were calculated. Finally, the G' digraph is calculated from each weighted directional relation that $n_f \rightarrow n_j$ on relation R_f is calculated by using (9) (see Fig. 5).

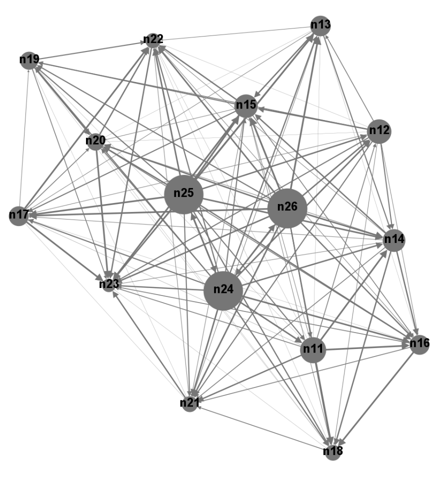

Fig. 5. The first iteration of digraph G' reconstruction with the fusion elements emerged, and the weighted distribution was calculated.

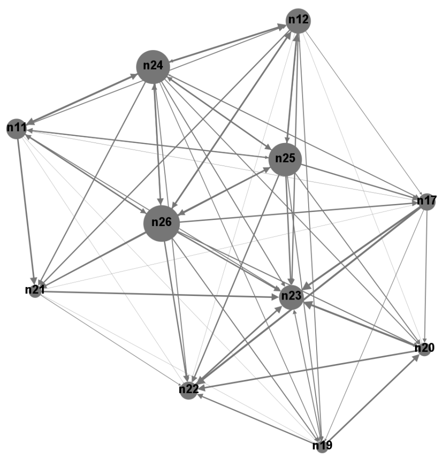

Fig. 6. The second iteration of digraph G'' reconstruction with the fusion elements and weighted distribution was calculated.

In a third workshop, based on G' digraph, the design group defined a problem criterion from (n_{25}, n_{26}) elements. The generative tool establishes a dialogue space for sense-making between the design group. The common ground interpretation based on weighted centrality, thus, following fusion relations: $n_{24} \rightarrow (n_{16}, n_{18})$, $n_{25} \rightarrow n_{13}$, and $n_{26} \rightarrow n_{14}$. Besides, the element n_{15} complements (n_{25}, n_{26}) fusion elements. Thus, the weighted relation is distributed with the same value in a G'' digraph.

The method is compared between G and G'', based on the analysis of the density of each digraph that represents the connectivity among nodes. For G is equal to $\Delta = 0{,}445$, and G'' is equal to $\Delta = 0{,}573$ is calculated by using (1), the results infer that the connectivity nodes from G'' increases the communication with all other nodes to G digraph.

D. *Develop a structural self-interaction matrix (SSIM).*

To explore the elements affecting a contextual relationship, pair-wise relationships among the system elements underweighted relation consideration. This matrix represents the perception that wise pair correlation directed relationship. By considering each contextual element relationship, four symbols were used to represent the relationship type (see Table IV).

E. *Develop a reachability matrix and driver power and dependence.*

Based on the SSIM, a binary matrix that reflects the directed relationships between the elements is transformed into a binary matrix. By applying four rules, a reachability matrix is obtained. The reachability matrix for the problem under consideration is obtained by incorporating transitivity (see Table V).

TABLE IVV
STRUCTURAL SELF-INTERACTION MATRIX (SSIM)

SN	n23	n22	n21	n20	n19	n17	n12	n26	n25	n24
n11	0,43 → V	0,14 → O	0,71 → X	0,00 → O	0,14 → O	0,17 → O	0,43 → V	0,56 → X	0,36 → A	0,66 → X
n24	0,47 → V	0,43 → V	0,56 → A	0,44 → V	0,37 → V	0,45 → V	0,79 → X	0,66 → X	0,63 → X	
n25	0,63 → V	0,60 → V	0,21 → O	0,45 → V	0,46 → V	0,60 → X	0,74 → V	0,65 → V		
n26	0,63 → A	0,61 → V	0,57 → V	0,50 → V	0,48 → A	0,61 → X	0,74 → V			
n12	0,57 → V	0,14 → O	0,57 → A	0,14 → O	0,43 → V	0,29 → O				
n17	0,86 → X	0,86 → X	0,14 → O	0,43 → V	0,29 → O					
n19	0,43 → V	0,57 → A	0,14 → O	0,71 → X						
n20	0,86 → X	0,71 → X	0,00 → O							
n21	0,71 → X	0,29 → O								
n22	0,71 → X									

TABLE V
THE REACHABILITY MATRIX

SN	n11	n24	n25	n26	n12	n17	n19	n20	n21	n22	n23	Driver power
n11	1	1	0	1	1	0	0	0	1	0	1	6
n24	1	1	1	1	1	0	1	1	0	1	1	9
n25	1	1	1	1	1	1	1	1	0	1	1	10
n26	1	1	0	1	1	1	0	1	1	1	0	8
n12	0	1	0	0	1	0	1	0	0	0	1	4
n17	0	0	1	1	0	1	0	1	0	1	1	6
n19	0	0	0	0	0	0	1	1	0	0	1	3
n20	0	0	0	0	0	0	1	1	0	1	1	4
n21	1	1	0	0	1	0	0	0	1	0	1	5
n22	0	0	0	0	0	1	1	1	0	1	1	5
n23	0	0	0	1	0	1	0	1	1	1	1	6
Dependence	5	6	3	6	6	5	6	8	4	7	10	

F. *Develop digraph.*

To classify the elements into level partitioning of the ISM structure. For this purpose, two sets are associated with each element of the system: a reachability set, which is a set of all elements that can be reached from the element, and an antecedent set, which is a set of all elements that the element can reach element. Subsequently, the intersection of these sets is derived for all elements. After the identification of the top-level elements, these are discarded from the other remaining elements. Table VI shows the different elements representing the various levels of the final model for the problem under consideration.

As a result, the reachability set for a top-level element will consist of the element itself and any other elements within the same level which the element may reach. Initial digraph comprising of transitive or indirect links is constructed by nodes and line of edges. The final digraph (see Fig. 7) is developed by eliminating the indirect links from the initial digraph and is transformed into an ISM model. This hierarchy model represents the connection between the elements along with their associated problem direction.

TABLE VV
LEVEL PARTITIONS TABLE

SN	Reachability set	Antecedent set	Intersection set	Level
n20	n19, n20, n22, n23	n24, n25, n26, n17, n19, n20, n22, n23	n19, n20, n22, n23	I
n17	n25, n26, n17, n20, n22, n23	n25, n26, n17, n22, n23	n25, n26, n17, n22, n23	II
n19	n19, n20, n23	n24, n25, n12, n19, n20, n22	n19, n20	II
n22	n17, n19, n20, n22, n23	n24, n25, n26, n17, n20, n22, n23	n17, n20, n22, n23	II
n23	n26, n17, n20, n21, n22, n23	n11, n24, n25, n12, n17, n19, n20, n21, n22, n23	n17, n20, n21, n22, n23	II
n11	n11, n24, n26, n12, n21, n23	n11, n24, n25, n26, n21	n11, n24, n26, n21	III
n12	n24, n12, n19, n23	n11, n24, n25, n26, n12, n21	n24, n12	III
n21	n11, n24, n12, n21, n23	n11, n26, n21, n23	n11, n21, n23	III
n24	n11, n24, n25, n26, n12, n19, n20, n22, n23	n11, n24, n25, n26, n12, n21	n11, n24, n25, n26, n12	IV
n26	n11, n24, n26, n12, n17, n20, n21, n22	n11, n24, n25, n26, n17, n23	n11, n24, n26, n17	IV
n25	n11, n24, n25, n26, n12, n17, n19, n20, n22, n23	n24, n25, n17	n24, n25, n17	V

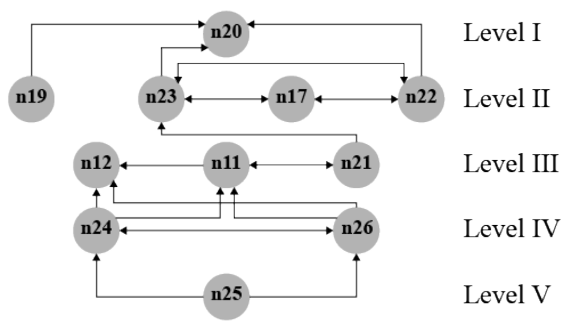

Fig. 7. Diagraph of multidisciplinary co-exploring criteria for motor impairment based on case study applied.

The driver power and dependence diagram into four sectors (see Fig. 8) helps to conquer the classification of different elements. This diagram gives visions about the relative significance and the interdependencies for enhancing the capabilities of the person with disabilities to social integration through professional labor as a productive activity. Also, it provides a valuable understanding for decision-making to problem-solving in the design group.

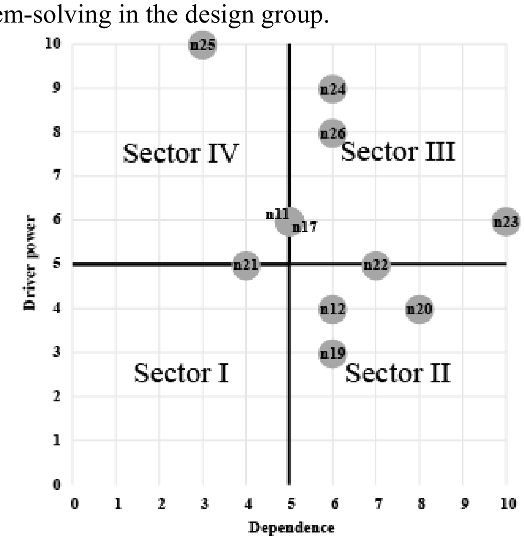

Fig. 8. The driver power and dependence diagram of multidisciplinary co-exploring criteria for motor impairment based on case study applied.

VII. COMPARISON ANALYSES

A comparison analysis was conducted in this section to validate the effectiveness of the proposed method.

First, establishing a collective sense-making between elements stage into an ISM process establishes a group of centrality weighted degree relation elements as dynamic collective dialogue space. The proposes allowed increases communication action between disciplines and person-user oriented to the collective decision-making process. The connectivity of the graphs is compared with the density of each digraph.

The elements fusion based on a collective sense-making between actors consolidated a set of elements, with a high driver power to identify messages categorizing a problem. Besides, the fusion elements intercommunicated multiple messages and decreased the complexity of the system. The cognitive process element is located in level V, and the workplace and executing process elements are located in level IV. These levels are the most potent influence among other elements of the system.

Second, the analyses obtained from the ISM and MICMAC methods observed that the fusion elements become the necessary categories for the decision-making process. For ISM presents that emerges collective elements workplace (n_{24}), cognitive process (n_{25}), and executing process (n_{26}) help to determine a path for reducing complex relationships among multiple messages.

Likewise, MICMAC illustrates that the collective element of workplace (n_{24}) is located in sector IV, which needs particular attention because it can condition the rest of the system as the independent variable. Cognitive process (n_{25}) and executing process (n_{26}) are collective elements located in sector III, which needs proactive consideration because any action made by these elements will affect others and feedback on themselves in the system as linkage variables.

VIII. CONCLUSION

This paper proposes a collective sense-making between elements stage with heterogeneous information, which finds the most reasonable decision-making alternatives. In the proposed method, the diverse data transformed into a collective form to be included in an ISM method that establish a group of elements from centrality weighted degree relation as dynamic collective dialogue space.

The comparisons of the proposed method with the traditional ISM model are conducted to show the advantage of the proposed model. The integration of the ISM and MICMAC approach may help identify and classify the effective elements that reveal the direct and indirect effects of the problem-solving process.

This paper presents a reduction of a complex system as an alternative to make visible the collective ideas of a group of people with a multidisciplinary approach. However, it is recognized that those collective emergent elements that can be included in the original system increase the complexity of the system. Therefore, this work incites other researchers to approach the thematic from the dialogue of knowledge from heterogeneous information to empower the unification of the ideas of the participants in the decision-making process.

References

[1] P. Abellard, A. Abellard, J. Gangloff, y A. Ciulli, «Atoll: an Elderly Housing Co-Design Software Tool», Nonpharmacol. Ther. Dement., vol. 3, n.o 2, pp. 97-103, 2012.

[2] S. Artoni et al., «Technology-enhanced ABA intervention in children with autism: a pilot study», Univers. Access Inf. Soc., vol. 17, n.o 1, pp. 191-210, mar. 2018, doi: 10.1007/s10209-017-0536-x.

[3] R. D. Debrah, R. de la Harpe, y M. K. M'Rithaa, «Design probes and toolkits for healthcare: Identifying information needs in African communities through service design», Des. J., vol. 20, n.o sup1, pp. S2120-S2134, jul. 2017, doi: 10.1080/14606925.2017.1352730.

[4] R. D. Debrah, R. de la Harpe, y M. K. M'Rithaa, «Exploring design strategies to determine information needs of caregivers», 7th Int. DEFSA Conf. Proc., pp. 67-77, 2015, doi: 978-1-77012-137-9.

[5] J. Li, J. Zhang, W. Ge, y X. Liu, «Multi-scale methodology for complex systems», Chem. Eng. Sci., vol. 59, n.o 8-9, pp. 1687-1700, abr. 2004, doi: 10.1016/j.ces.2004.01.025.

[6] J. L. Moreno y H. H. Jennings, «Statistics of Social Configurations», Sociometry, vol. 1, n.o 3/4, p. 342, ene. 1938, doi: 10.2307/2785588.

[7] S. Wasserman y K. Faust, Social Network Analysis: Methods and Applications. Cambridge University Press, 1994.

[8] P. H. Jones, «Systemic Design Principles for Complex Social Systems», en Social Systems and Design, G. S. Metcalf, Ed. Tokyo: Springer Japan, 2014, pp. 91-128.

[9] D. A. Norman y P. J. Stappers, «DesignX: Complex Sociotechnical Systems», She Ji J. Des. Econ. Innov., vol. 1, n.o 2, pp. 83-106, 2015, doi: 10.1016/j.sheji.2016.01.002.

[10] P. Jones, «Contexts of Co-creation: Designing with System Stakeholders», 2018, pp. 3-52.

[11] R. Murphy y P. Jones, «Leverage analysis», FormAkademisk - forskningstidsskrift Des. og Des., vol. 13, n.o 2, pp. 1-25, ene. 2020, doi: 10.7577/formakademisk.3384.

[12] R. J. A. Murphy y P. Jones, «Design management for wicked problems: Towards systemic theories of change through systemic design», en 22st DMI: Academic Design Management Conference, 2020, pp. 1-16.

[13] Z. Zhang, C. Guo, y L. Martinez, «Managing Multigranular Linguistic Distribution Assessments in Large-Scale Multiattribute Group Decision Making», IEEE Trans. Syst. Man, Cybern. Syst., vol. 47, n.o 11, pp. 3063-3076, nov. 2017, doi: 10.1109/TSMC.2016.2560521.

[14] G. Li, G. Kou, y Y. Peng, «A Group Decision Making Model for Integrating Heterogeneous Information», IEEE Trans. Syst. Man, Cybern. Syst., vol. 48, n.o 6, pp. 982-992, jun. 2018, doi: 10.1109/TSMC.2016.2627050.

[15] J. N. Warfield, «Developing Subsystem Matrices in Structural Modeling», IEEE Trans. Syst. Man Cybern., vol. SMC-4, n.o 1, pp. 74-80, 1974, doi: 10.1109/TSMC.1974.5408523.

[16] M. Godet, «Introduction to la prospective», Futures, vol. 18, n.o 2, pp. 134-157, abr. 1986, doi: 10.1016/0016-3287(86)90094-7.

[17] R. Oliva, «Model structure analysis through graph theory: partition heuristics and feedback structure decomposition», Syst. Dyn. Rev., vol. 20, n.o 4, pp. 313-336, 2004, doi: 10.1002/sdr.298.

[18] U. Khan y A. Haleem, «Smart organisations: modelling of enablers using an integrated ISM and fuzzy-MICMAC approach», Int. J. Intell. Enterp., vol. 1, n.o 3/4, p. 248, 2012, doi: 10.1504/IJIE.2012.052556.

[19] V. Sharma, S. Grover, y S. K. Sharma, «Analyzing the barriers affecting the effective utilization of quality tools and techniques using integrated ISM approach», Manag. Sci. Lett., vol. 7, n.o 11, pp. 525-540, 2017, doi: 10.5267/j.msl.2017.8.003.

[20] I. Dawood y J. Underwood, «Prioritising Variables of SMEs / Private Sector through Interpretive Structural Model (ISM)», en TG65 & W065 - Special Track 18th CIB World Building Congress, 2010, pp. 146-160.

[21] S. Karadayi-Usta, «An Interpretive Structural Analysis for Industry 4.0 Adoption Challenges», IEEE Trans. Eng. Manag., vol. 67, n.o 3, pp. 973-978, ago. 2020, doi: 10.1109/TEM.2018.2890443.

[22] K. A. Rade, V. A. Pharande, y D. R. Saini, «Interpretive Structural Modeling (ISM) for Recovery of Heat Energy», Int. J. Theor. Appl. Mech., vol. 12, n.o 1, pp. 83-92, 2017.

[23] T. Mattelmäki, Design Probes. University of Art and Design Helsinki, 2006.

[24] T. Mattelmäki, «Probing for co-exploring», CoDesign, vol. 4, n.o 1, pp. 65-78, mar. 2008, doi: 10.1080/15710880701875027.

[25] E. B.-N. Sanders y P. J. Stappers, «Co-creation and the new landscapes of design», CoDesign, vol. 4, n.o 1, pp. 5-18, mar. 2008, doi: 10.1080/15710880701875068.

[26] E. B.-N.Sanders, «From user-centered to participatory design approaches», en Design and the social sciences, London: CRC Press, 2002, pp. 1-8.

[27] J. N. Warfield, «Toward Interpretation of Complex Structural Models», IEEE Trans. Syst. Man Cybern., vol. 4, n.o 5, pp. 405-417, 1974, doi: 10.1109/TSMC.1974.4309336.

[28] D. M. Lee, Structured Decision Making with Interpretive Structural Modeling (ISM): Implementing the Core of Interactive Management. Canada: Sorach Inc., 2007.

[29] I. Oosterlaken, «Design for Development: A Capability Approach», Des. Issues, vol. 25, n.o 4, pp. 91-102, oct. 2009, doi: 10.1162/desi.2009.25.4.91.

[30] M. Hassenzahl, «Experience Design: Technology for All the Right Reasons», Synth. Lect. Human-Centered Informatics, vol. 3, n.o 1, pp. 1-95, ene. 2010, doi: 10.2200/S00261ED1V01Y201003HCI008.

[31] L. C. Freeman, «Centrality in social networks conceptual clarification», Soc. Networks, vol. 1, n.o 3, pp. 215-239, ene. 1978, doi: 10.1016/0378-8733(78)90021-7.

[32] T. Opsahl, F. Agneessens, y J. Skvoretz, «Node centrality in weighted networks: Generalizing degree and shortest paths», Soc. Networks, vol. 32, n.o 3, pp. 245-251, jul. 2010, doi: 10.1016/j.socnet.2010.03.006.

[33] G. P. Patil, «Weighted Distributions», en Wiley StatsRef: Statistics Reference Online, Chichester, UK: John Wiley & Sons, Ltd, 2014, pp. 1-11.

[34] B. P. Singh y U. D. Das, «Some Statistical Properties of a Weighted Distribution and Its Application to Waiting Time Data», Asian J. Probab. Stat., vol. 9, n.o 1, pp. 1-12, sep. 2020, doi: 10.9734/ajpas/2020/v9i130216.

[35] M. E. J. Newman, «Scientific collaboration networks. II. Shortest paths, weighted networks, and centrality», Phys. Rev. E, vol. 64, n.o 1, p. 016132, jun. 2001, doi: 10.1103/PhysRevE.64.016132.

[36] Sushil, «Interpreting the Interpretive Structural Model», Glob. J. Flex. Syst. Manag., vol. 13, n.o 2, pp. 87-106, jun. 2012, doi: 10.1007/s40171-012-0008-3.