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A critical analysis of sustainable micro-manufacturing from the perspective of the triple bottom line: a social network analysis

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Abstract

Nowadays, substantial improvements in sustainable micro-manufacturing are explicitly addressed based on the triple bottom line (TBL) concept. However, strong criticisms are leveled for the applications of TBL as immense complexities of inner relationships of items and dimensional relationships within TBL, which they cause an inefficacy of accessing critical information in introducing the TBL concept to sustainable micro-manufacturing. In this study, social network analysis (SNA) is used for developing a TBL network of sustainable micro-manufacturing to find out precise meanings of individual items of various dimensions of TBL and the relationships between them. The main metrics of the dominant items of TBL such as in-degree, out-degree, betweenness centrality and closeness centrality are detailly discussed with 16 nodes for three dimensions in the TBL networks. The related findings are further analyzed to reveal the current situation, technical gaps and chances for the sustainable development of the micro-manufacturing sector. This study aims to reveal the relationship between the items of TBL of micro-manufacturing, and delivers the significant roles of the items of TBL according to the findings of metrics and visual analyses for sustainable micro-manufacturing, supporting micro-manufacturing sectors to implement effective sustainable strategies for production activities.

Keywords: Micro-manufacturing; Triple bottom line; Sustainable development; Social network analysis

1. Introduction

Manufacturing is one of the dominant contributors to the consumption of energy and natural resources under consideration of major sectors. Being an essential component in the manufacturing sector, micro-manufacturing begins to be exploited, leading to a significant increase in the production volume of micro-components as well as a fabrication tool of scientific innovations for highly technological products. Referring to the report from Mounier (2014), the market for micro-electronic and mechanical systems values about 25 billion dollars. For such a vast economic proportion of our community, micro-manufacturing has engendered environmental concerns by the public. The impact of micro-manufacturing on the environment is similar to that of traditional manufacturing (Modica et al., 2011; Yip and To, 2018). The life cycle assessment of micro-manufacturing has proved that consumptions of raw material and energy and generations of waste are relatively high in micro-manufacturing (De Grave et al., 2007; De Grave and Olsen, 2006). Because of conspicuous resource consumptions by micro-manufacturing, micro-manufacturing units are responsible to work out sustainability strategies. Nowadays, sustainable micro-manufacturing is executed meticulously by manufacturing sectors due to increments of pressures from society, stakeholders and related customers. An assurance for the public towards sustainability development of micro-manufacturing leads the industries to reformulate their strategies to retain operations and comprehensive services for continuous developments (Shankar et al., 2017).

The revolution towards sustainable micro-manufacturing is not only a single aspect for the manufacturing sectors, different dimensions in terms of economy, society and environment should also be considered, which this concept is related to one of the essential sustainable frameworks: triple bottom line (TBL). TBL comprises three components which are social equity, economy, and environment. The words "people”, “planet”, and “profit" are often used to denote TBL and the desired goals of sustainability. Although TBL is frequently employed to be a framework for sustainable development of manufacturing sectors, there has always criticisms about the difficulties of executing it in practical situations from the firms. Manufacturing sectors experience undue complications because of complicated relationships between items of TBL. High complexity is mainly caused by the intricate inter-relationships between the inner dependences or items within TBL (Tullberg, 2012). Brown et al. (2006) held opinions on TBL that the complicated inter-relationships among the items in TBL distorted the benefits of sustainable development. Because of the complicated inter-relationship between items, systematic and scientific analysis of TBL are problematic. The firms turn to be compliant with spectators and adjust the policy to cope with the external pressures and conduct actions with an emphasis on particular components of TBL in order to comfort spectators (Tullberg, 2012). The inter-relationships of items of TBL are varied on occasion as the definitions and the relationships are developed case by case with the concerns of the interests and needs of the community (Mc Kenzie, 2004). By using the TBL concept with those varied definitions and relationships, the community's and stakeholder's perceptions on the sustainable micro-manufacturing are disrupted, undergoing researches is further affected. In this regard, researchers and units should apply a proper modified TBL framework in order to ensure their competitive advantages.

Because of the complexity of the inter-relationship of items of the TBL framework, limitations have been imposed on the micro-manufacturing sectors. In this study, social network analysis (SNA) is applied for analyzing and clarifying the complicated inter-relationship between items of TBL. During conducting SNA, the various items of three dimensions of TBL for micro-manufacturing would be set as nodes with connections by ties, and consequently, the metrics were obtained. By conducting the metric and visual analyses of the TBL network corresponding to micro-manufacturing and properly interpreting the metrics determined from SNA, hidden information and the interrelationship between items could be revealed in a simple format. The significant roles of the items of TBL for supporting sustainable mico-manufacturing could be demonstrated afterward. With an adequate understanding of the items within three dimensions of TBL for micro-manufacturing, the particular items of TBL which are worth for micro-manufacturing firms to invest in can be identified to move forward to sustainability. This study contributes to providing a critical analysis of sustainable development of micro-manufacturing sectors for implementing successful sustainable micro-manufacturing strategies under full consideration of the TBL concept, also offering the fast track for optimizing the influences of adjustments of items of TBL when conducting sustainable micro-manufacturing strategies.

2. Theory

2.1 Triple Bottle Line

TBL normally represents the three major dimensions of sustainable development: society, environment and economy. According to the United Nations (Assembly, 2005), it indicated that successful achievement of sustainable development is highly dependent on the balance between the items of TBL: environment, social equity and economic demands. Normally, the three dimensions are framed as below for manufacturing nowadays:

Profit: The profit component of TBL is commonly denoted as productivity, return and benefit of the manufacturing sectors. The scope of this component may extend to the financial performances of the manufacturing sector including return on asset and return on investment.

Planet: Literatures stated that that the planet element of TBL involves the influences of the activities from manufacturing sectors on both natural and non-natural systems, which include pollutant emissions, resource and energy consumptions from the manufacturing processes.

People: When "people" of TBL is considered, it commonly relates to how manufacturing sectors could contribute to society. Some manufacturing sectors think of ways about offering environmental activities with an added value to the community such as career retention, volunteerism and charitable contributions (Schulz and Flanigan, 2016), or the ways of providing benefits to employees including education, training and enjoyment of social resources.

2.2 Social network analysis

SNA has a long history that is traced back to the 1930s. Nowadays it is applied to evolutionary developments for mainstream topics of our society such as sociology, anthropology, and business analyst. SNA offers theories and analytical techniques for understanding a wide range of matter behavior changes as actors interacting with certain others. A network constructed by SNA is composed of a set of nodes (network members) which the nodes are connected (tied) with one or more types of nodes, forming various types of relations (Wasserman and Faust, 1994). SNA makes use of the constructed network as an entire block of the investigated area, the block consist of connections of different network members. The identification and conceptualization of the nodes are the main procedures to construct a network in SNA (Wasserman and Faust, 1994). Nodes, of SNA, are the network members that are connected by the relationships, which those relationships generate a pattern or a map. The nodes are normally the factors that involve in the examined targets. For the scale of node-level, centrality displays the relative importance of nodes at the constructed network.

3. Conceptual interpretation of metrics for TBL of micro-manufacturing

3.1 Conceptual interpretation of metrics

A conceptual interpretation is a necessary process in SNA, it offers accurate meanings of defined nodes, edges between items in the developed network. The metrics of every network have different meanings, which depend on the research questions and investigational targets of the researches. In this study, the TBL framework of micro-manufacturing is constructed by SNA, Table 1 shows the overview of key metrics and the specific roles of the items of the TBL framework in micro-manufacturing. The contents of Table 1 are referred to the implications from the definition of the main metrics of SNA, which are in-degree, out-degree, betweenness and closeness, which the definitions of metrics are detailly discussed in section 3.2. The integration of the definitions of metrics from SNA with the contents of sustainable micro-manufacturing will give out a unique implication and the conceptual framework of sustainable micro-manufacturing. Consequently, the corresponding TBL network and the implications of the nodes/items in the TBL network with corresponding highest values of particular metrics and the context of modeling TBL of micro-manufacturing are demonstrated. We combine the definitions of particular metrics with that of the nodes and assume the resource flowing within the network, demonstrating the interactions of the node/network members and constructing the implications of dominant nodes with the highest values of particular metrics.

Table 1. The overview of key metrics and the corresponding roles of the items of TBL for micro-manufacturing

Centrality metric	Meanings for the TBL framework	Conceptual definitions of TBL framework in micro-manufacturing	Implications for central nodes in TBL*	
			Role	Description
In-degree	Items of TBL be influenced	The degree of reacting incoming influences/resources from other items within TBL	Influenced	To consider all of the items in TBL, the level of absorbing the integrated influences/resources from upstream items in TBL when conducting production activities

Out-degree	Items influence other items within TBL	The degree of influencing power of the item to other items within TBL	Influencer	To distribute the influences across other items within TBL when conducting production activities
Betweenness	Items located between a pair of non-adjacent items within TBL	The ability for an item to monitor other items to transfer their effects between each other	Gatekeeper	To mediate the influences between items within TBL when conducting production activities, for optimizing the influences of other items with contradictive trends; providing the gateway for the action fulfilling the aims of various dimensions of TBL simultaneously
Closeness	Items enable to influence other items within the network without relying on other items for transferring information or resources	An item of TBL having the closest/ most immediate effects to influence other items within the TBL network	Facilitator	To easily access and explore the performance of another item within TBL by controlling the nodes with high closeness when conducting production activities

*Implications are given to the high value of the particular metric

3.2 SNA Metrics

Degree centrality is determined by the ratio of the number of direct ties to a node. Degree centrality C_D is calculated by:

$$C_D(n_i) = \sum_i x_{ij} = \sum_j x_{ji} \quad (1)$$

Where x_{ij} is the positive number, it is equal to 1 if there exists a connection between n_i and n_j. Degree centrality is normally normalized as a percentage in SNA. Degree centrality expresses the causes and origins of actions from the network members within the network.

The calculation of closeness centrality is based on the geodesic distance $d(n_i,n_j)$ between two nodes, which is expressed as the shortest length of the path between node n_i and node n_j (Frenken, 2000; Hakimi, 1964). The closeness centrality C_c is expressed as:

$$C_c(n_i) = \left[\sum_{j=1}^{g} d(n_i,n_j)\right]^{-1} \quad (2)$$

where $\sum_{j=1}^{g} d(n_i,n_j)$ is the total distance of node n_i connected with other nodes. Closeness centrality quantitatively states the level of closeness of one network member to other network members within the same network quantitatively.

Betweenness centrality determines the level of an individual network member having the shortest path between all the combinations of the pairs of network members. When the network members with relatively high betweenness centrality are isolated by external forces, other dependent network members will be blocked to communicate with other connected network members. Between centrality C_B is determined by

$$C_B(n_i) = \sum_{j<k} \frac{g_{jk}(n_i)}{g_{jk}} \quad (3)$$

where g_{jk} is the total number of geodesic connections between two nodes, $g_{jk}(n_i)$ is the number of geodesic connections including node n_i.

4. Methodology

4.1 Identification of nodes for TBL network of micro-manufacturing in SNA

A systematic literature review would be employed in this study for getting the nodes in SNA. A systematic literature review is an approach to review scientific papers to guarantee the transparency and integrity of the conclusions (Tranfield et al., 2003). Systematic literature review composed of five steps: (1) question formation, (2) locating studies, (3) study selection and determination, (4) analysis and synthesis and (5) reporting the results (Garza-Reyes, 2015). Steps (1-3) would be discussed in detail in section 4.1.1. For steps 4-5, the analysis approach is SNA and the interpretation of metrics is given to show the TBL framework of micro-manufacturing. Figure 1 shows the steps of systematic literature review in this study.

Step 1

Step	Objective	Approach	Tool/ Source
Question Formulation	Identifing the research questions which are the main investigation objects in the researches		
Locating Studies	Locating and choosing the relevant literature, reviewing and determining them	Use appropreiate electronic databases	Elsevier, Willey and Taylor and Francis
Study selection and determination		Define the duration of the papers	2009-2019
		Define the inclusion and exclusion criteria for the selection	Inclusion: The papers describe micro-manufacturing focusing on triple bottom line; 2 Peer review articles if papers in proceedings or international conference
			Exclusion: 1.The papers appear after the first search, but the titles do not relate to micro-manufacturing. 2. After the exclusion of the papers with unrelated titles in criteria (1), the abstract of the non-excluded papers are read, the papers are selected only for those directly or in-directly related to "sustainability development of manufacturing using TBL"
		Define the strings used in the searches	1. "micro-manufacturing" + "sustainability" for Elsevier; "manufacturing" + "triple bottom line" for Willey and Taylor and Francis
Analysis	Analysing the selected researches	Choose the approach for synthesizing and analyzing the searched papers	Social network analysis
Reporting the results	Reporting the findings		

Step 5

Figure 1. Steps of systematic literature review of this study

4,2 Locating studies, study selections and determinations

In this study, the papers are found by searching the designed strings in the electronic databases of several publishers focusing on scientific articles. The electronic databases of several publishers include Elsevier, Taylor and Francis and Wiley. For the searched strings, the search terms "micro-manufacturing" and "triple bottom line" were used for the publisher Elsevier. In order to make the balance between sustainability and triple bottom line, for the publishers Willey and Taylor and Francis, we especially search for the sustainability development of micro-manufacturing using TBL, however, there were limited numbers of researches about micro-manufacturing using TBL. Therefore, the search strings were rephrased from "micro-manufacturing" to "manufacturing". The contents are distinguished between micro-manufacturing from manufacturing using authors' expertise. On the other hand, the first screening of the searched papers would be conducted by reading the title of the resulting papers, once the papers' title does not relate to micro-manufacturing, the papers would be excluded even they appear in the searching results (as 1. micro-manufacturing in literature sometimes means manufacturing activities from small enterprises, it is significantly different from the meaning of micro-manufacturing which is a subtractive mechanical approach for shaping raw material into the desired shape, and 2. the word “triple bottom line” always appears dominantly in the title of searched papers for all types of manufacturing activities). After that, the papers would be selected by the scope of the journals in the searching results in order to include the searched papers with the correct scope, which the journals are Science Citation Indexed journals and considered as the high influential scientific references in the academic area. For Elsevier, the journals “Journal of Cleaner Production”, “Procedia CIRP”, “Journal of Materials Processing Technology”, “Journal of Manufacturing Processes”, “CIRP Annals”, “Procedia Engineering” are included; For Willey, the journals “Journal of Industrial Ecology” and “Environmental Progress & Sustainable Energy” are included; For Taylor and Francis, the journals “International Journal of Production Research”, and “International Journal of Sustainable Engineering” are included. Referring to the above searching criteria mentioned in this section, the selected papers are shown in Figure 2, the total of paper selected was 147.

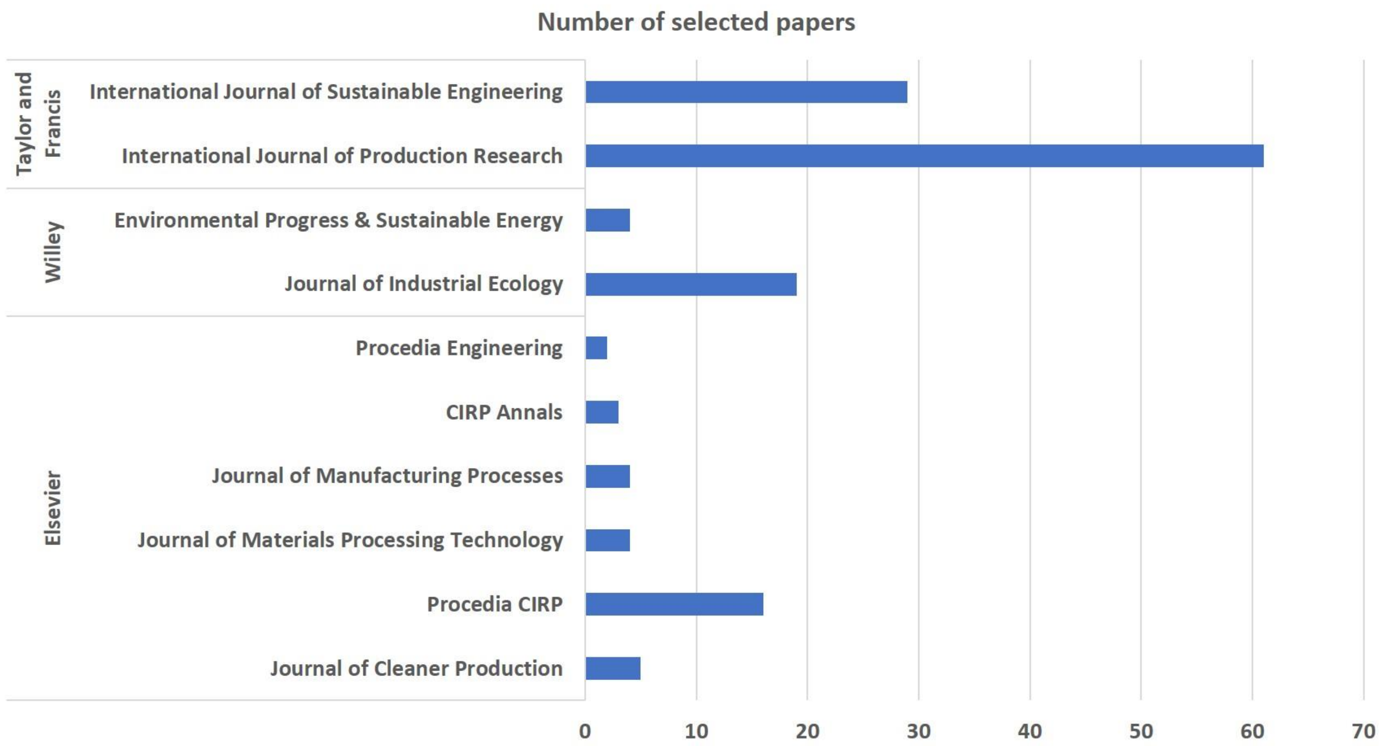

Figure 2. The number of selected papers for each journal

After extracting information from the selected journals, the factors were identified and the general explanations of those factors were established, which are shown in Table 2. The illustration graph of TBL with items is shown in Figure 3, and the general descriptions of those items in manufacturing are shown in Table

2. It is worth noting that the definitions of the items are not referred to the literature source, as they are the general definitions of the terms which are not affected by the time period. The acronym of the nodes/items employed throughout this study are referred to the content of Table 2.

Table 2. The general descriptions of nodes and factors of TBL of micro-manufacturing explained in the literature

Dimension	Nodes/ factors	General descriptions
Economic	Production Cost (PC)	● Cost-effective production requires flexible production facilities (Wulfsberg et al., 2010) ● Product is the cost per component or product (Alting et al., 2003) ● Product cost is required for developing a customized micro-assembly (Alting et al., 2003) ● Product cost considerations are also important at this stage since the major cost component is said to be the packaging (Senturia, 2007)
	Surface Quality (SQ)	● An achievement of optical surface qualities (Luo et al., 2005) ● Presented by the value of surface roughness normally
	Material Removal Rate (MRR)	● The amount of material removed per time unit, directly aiming at the process productivity ● Defined either as the volume removed per time, or the mass removed per time
	Cutting Tool Usage (CTU)	● Cutting tool materials have a decisive influence on cutting processes
	Tool Wear (TW)	● Cutting tool materials constitute a special group of tool materials because they must withstand extreme process conditions specifically for cutting (Grzesik, 2008). ● Tool wear is an issue during the machining of hard and difficult-to-cut materials since it negatively impacts the accuracy and finish of the produced part (Rahman et al., 2014). ● Tool wear associated with poor surface finish (Balazinski et al., 2012)
	Production management (PM)	● Production management is about optimally producing products mostly deploying resources as an asset for the entire organization (Greeff and Ghoshal, 2004). ● The level of consumption and resource allocation management (Wu, 2011).
Environment	Water Intensity (WI)	● Water efficiency stated what has been termed as traditional demand management, which focuses on the approach to reduce the amount of water using in a specific work (Tarhule, 2017).

	Energy Intensity (EI)	● Energy intensity is the amount of energy used per dollar of gross domestic product produced (Seo, 2017). ● Energy intensity is the total amount of energy requirement in production processes as a percentage of the total exported products from the production facility (Khalilpour, 2018).
	Lubricant use (LU)	● The lubricant used in fabrication processes.
	Usage of raw material (URM)	● Inputs for fabrication (Durante et al., 2015).
	Water Management (WM)	● Water management is a powerful approach to protecting public health from harmful contaminants (Kuo and Xagoraraki, 2017). ● Water management addressed social ideas and problems implicitly (Tarhule, 2017)
	Environmental Management (EM)	● Environmental management involves strategies for dealing with wastes (Cheremisinoff et al., 2013). ● An environmental management program is the roadmap of the organization for achieving environmental objectives and targets (Cheremisinoff et al., 2013).
	Carbon dioxide emission (CE)	● Carbon dioxide emissions associated warming of the atmosphere, having a profound impact (Houghton, 2005) ● Carbon dioxide is the primary greenhouse gas emitted through human activities (Houghton, 2005)
Social	Work Health (WH)	● The health issue of workers arising from the work environment (Clegg et al., 1989)
	Work Safety (WS)	● Safety at work is easy to use and will prevent workers from workplace accidents ● Provisions linked to health and safety duties at work
	Labor Law (LL)	● Labor laws are being revised to abolish job preservation and to guarantee equal opportunity employment and remuneration (Bluhm, 2001) ● The labor law provides a set of minimum labor standards (Tsogas, 2015)
	Training and Education (TE)	● A better deal with technological change that labor productivity is less adversely affected by the turmoil induced by technological transformations of the workplace (Hornstein et al., 2005) ● Less costly for labor to acquire the additional skills needed to use new technology (Bessen, 2016)

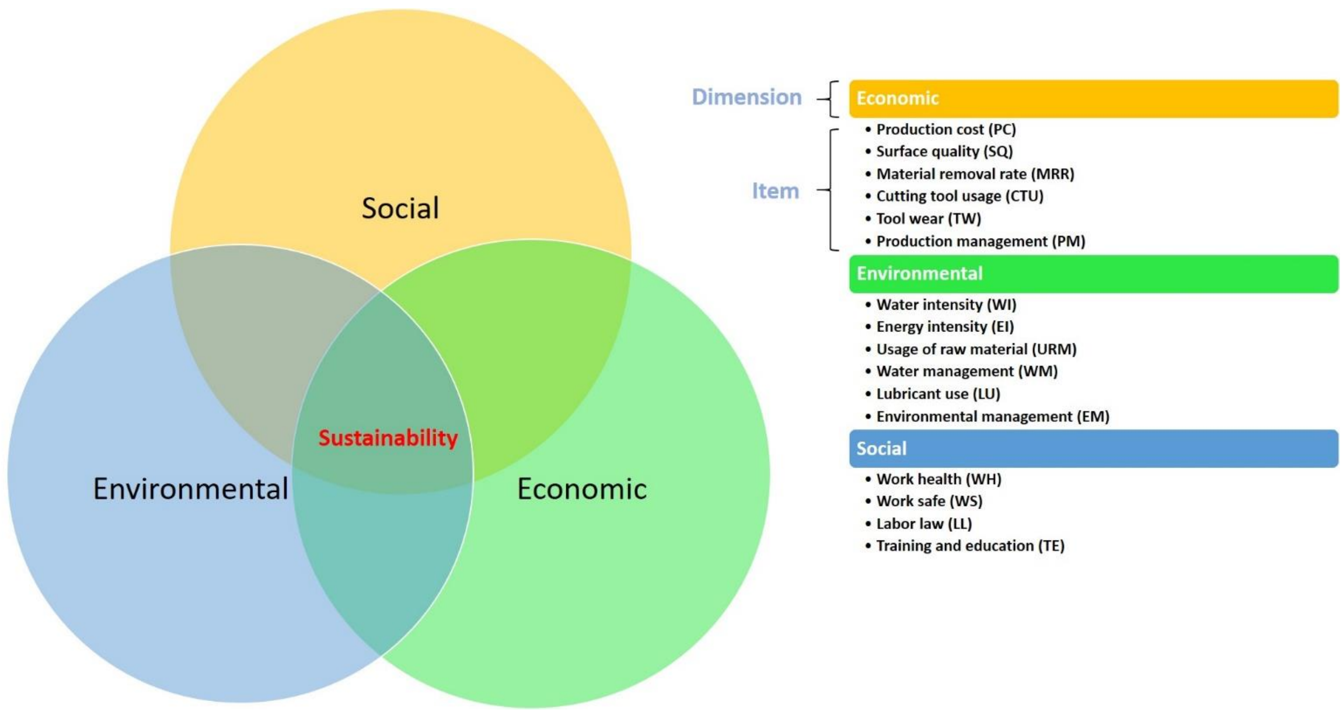

Figure 3. The illustration graph of TBL in micro-manufacturing with corresponding items

4.3 Relationship between nodes/ items in SNA

After defining the items/nodes for constructing the network of sustainable micro-manufacturing using SNA, the relationships between nodes are then required to explore. The relationships between nodes are determined by the author's expert with references from the literature. Two nodes have relationships and it would be represented as 1 in an interactive analysis as shown in Table 3. After that, the node relationships are input to the software NodeXL, which NodeXL has built in the library of popularly used graph metrics especially the metrics in the node-level and network-levels and cluster coefficient. Also, it enables to executes of various common algorithms to intelligently find out the clusters in the generated social networks.

Table 3. The interactive relationships between each node/item of micro-manufacturing for establishing TBL framework

	PC	SQ	MRR	CTU	TW	PM	LU	EI	URM	WM	EM	CE	WH	WS	LL	TE
PC	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
SQ	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0
MRR	1	1	0	1	1	1	1	1	1	1	1	1	0	0	0	0
CTU	1	1	1	0	1	0	0	1	0	1	0	1	0	1	0	1
TW	1	1	1	0	0	0	0	1	0	0	1	1	0	0	0	0
PM	1	0	1	1	0	0	1	1	1	1	1	1	1	1	0	1
LU	1	1	0	0	1	0	0	1	0	1	0	1	1	1	0	0
EI	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0

URM	1	0	1	1	0	0	1	1	0	1	0	0	1	1	0	1
WM	1	0	0	0	0	1	1	1	0	0	1	1	0	0	0	1
EM	1	0	0	0	0	1	1	1	0	1	0	1	0	0	0	1
CE	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0
WH	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1
WS	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1
LL	1	0	0	0	0	1	0	0	0	0	0	0	1	1	0	1
TE	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0

5. Results and Discussion

5.1 The network of micro-manufacturing with the TBL concept *constructed by SNA*

The items of TBL regarding micro-manufacturing were assigned as nodes and inputs for SNA. The group metrics were determined finally and are shown in Tables 4 - 6. The constructed TBL network by SNA is shown in Figure 4. The color of the vertex is used to classify the dimension of the group: social dimension - blue; environmental dimension – green, and economic dimension - orange. The size and opacity of the vertexes reflect the values of in-degree and out-degree of the nodes respectively.

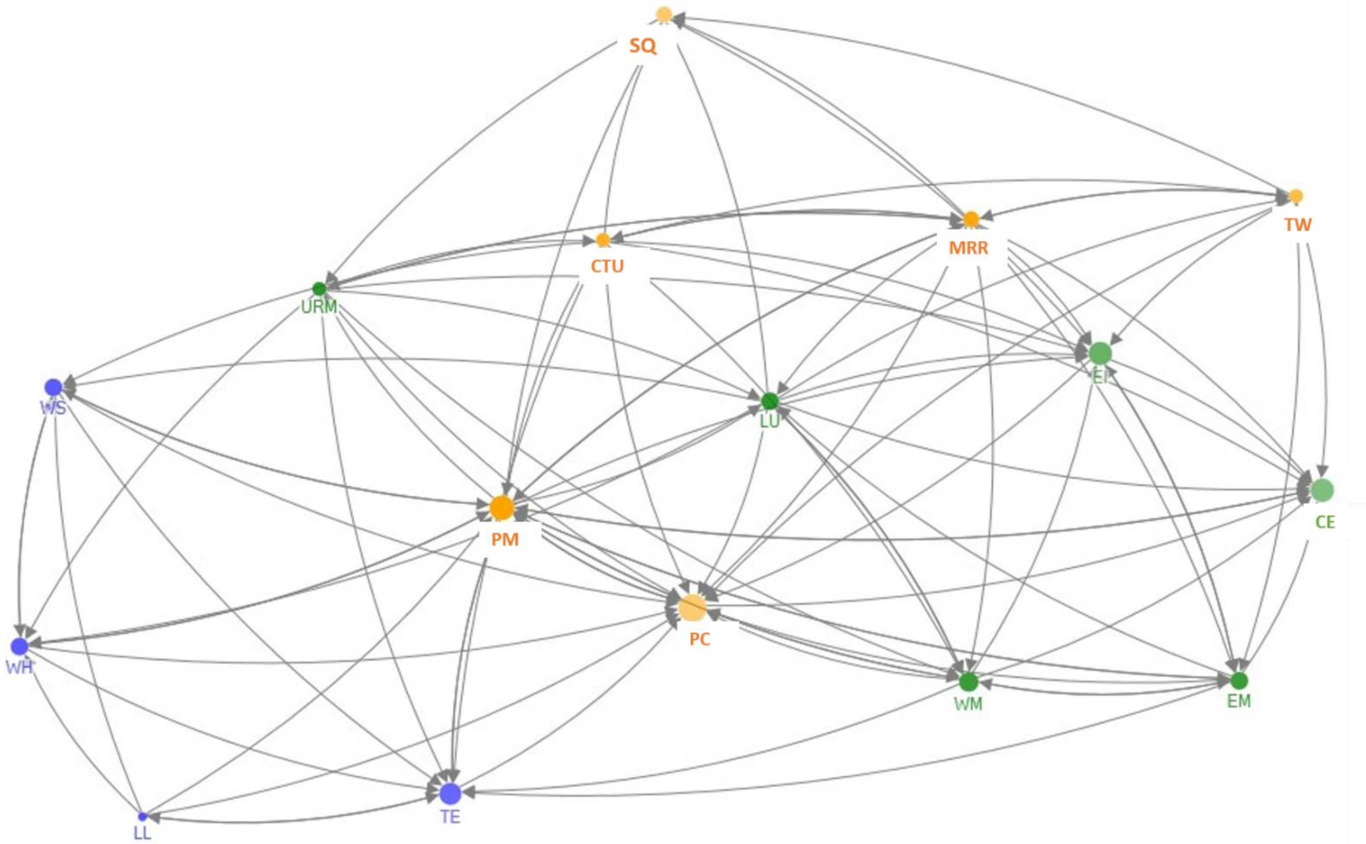

Figure 4. The constructed network of micro-manufacturing with the TBL concept by SNA

5.2 Group metrics analysis

The results of group metrics are shown in Tables 4-6. The results are generated from the software NodeXL, which delivers the results of the metrics in the both node- and network-levels using the network analysis theory. The environmental activities within the self-dimension and cross-dimension would be both investigated by accessing the group metrics. Edge number means the number of relationships built up by two items within the network. The edge numbers of self-dimension and cross dimensions are shown in Tables 5 and 6 respectively. According to Table 5, the edge numbers of economic-economic, environmental-environmental and social-social dimensions are 17, 16 and 8 respectively. The above results demonstrated that the numbers of environmental activity initiated by the items from the economic and environmental dimensions are relatively higher than that of the social dimension, implying the interactions of environmental activities inducing from the items of environmental and economic dimensions of micro-manufacturing are potentially dominant than that of the social dimension. Although the numbers of total edges in self dimension are higher for environmental and economic dimensions, it may be due to the relatively higher vertices (items) in these two dimensions and hence they induce a higher level of inter-interactions. In this case, the reciprocated edge ratio and the reciprocated vertex pair ratio should be considered in order to remove the effect of vertice number on the level of inter-relationship of items. The reciprocated edge ratio and the reciprocated vertex pair ratio mean the percentages of vertices having a reciprocal relationship and the percentage of edges having a reciprocal relationship respectively. According to Table 4, the numbers of the reciprocated edge ratio and the reciprocated vertex pair ratio for the social dimension are higher than that of the other two dimensions, which are 0.5 and 0.333 respectively. These two numbers imply that the level of influences inducing per item to another item at the same dimension in TBL is the largest for the social dimension.

Table 6 shows the numbers of relationships between crossing dimensions. Referring to Table 6, it is worth noting that the edge number for “economic- environment” is determined as 21, which is the highest among all the other pairs. Because of the nature of the directional constructed network, the highest of the edge number means the environmental activities of TBL are normally initiated by the items from the economic dimension, and the beneficial results are enjoyed by the items in the environmental dimension. Another noticeable observation from the results of Table 6 is, all the edge numbers involving the items of the social dimension are comparably small. The numbers of edges of “economic - social”, “social - economic” and “social - economic” are 5, 8 and 0 respectively. These numbers reveal that the environmental activities relating to the social dimension, regardless of initiation or the final target, are the least active among the other two dimensions. And it further shows the strong individual state of the social dimension in TBL. The environmental activities of the social dimension are rarely supported by or benefited to the other two dimensions in micro-manufacturing, also, the motivation of environmental activities in micro-manufacturing is rarely started by social needs. Sutherland et al. (2016) stated the same opinion that much more attention of our public has been paid to the economic and environmental dimensions nowadays, but they are far less offered to the social dimension for the sustainable development of manufacturing.

Table 4. The group metrics of economic, environmental and social dimensions of TBL in micro-manufacturing

Label	Vertices	Unique Edges	Total Edges	Reciprocated Vertex Pair Ratio	Reciprocated Edge Ratio	Maximum Geodesic Distance	Average Geodesic Distance	Graph Density
Economic	6	17	17	0.308	0.471	2	0.944	0.567
Environmental	6	16	16	0.231	0.375	2	0.944	0.533
Social	4	8	8	0.333	0.500	1	0.750	0.667

Table 5. The edge number established by items at the self-dimensions.

Dimension	Dimension	Edge number
Economic	Economic	17
Environmental	Environment	16
Social	Social	8

Table 6. The edge number established by items at non-identical dimensions.

Dimension	Dimension	Edge number
Economic	Environmental	21
Economic	Social	5
Environmental	Economic	12
Environmental	Social	6
Social	Economic	8

Social	Environmental	0

5.3 Node metrics analysis

5.3.1 In-degree

Figure 5 shows the values of in-degree of items of three dimensions of TBL in micro-manufacturing. Referring to Figure 5, the node with the highest in-degree is production cost, which value is 13. The highest value of in-degree for production cost denoted that production cost in sustainable micro-manufacturing is influenced by the highest number of environmental activities initiated from the items of the other dimensions, therefore, adjustments of environmental strategies on the other items for the sustainability development in micro-manufacturing would definitely influence production cost. Production cost is therefore unfairly dominant among all items in TBL of micro-manufacturing. Actually, it matches with the historical sustainable development of various sectors. Referring to literature, TBL is suffered from imbalanced attention so far (Hollos et al., 2012), the traditional focuses on economic performances of TBL framework had been extensively mentioned, emphasizing their effects on the environmental dimension (Min and Galle, 2001) and shifting the weight of TBL from the social dimension to the economic dimension (Schönsleben et al., 2016). Another observation would be made on the item with the lowest in-degree value. The item with the lowest value in in-degree is labour law, which its in-degree is 1. It means that labour law receives the least incoming influence from other items of the TBL network, or just simply say, it only receives the influences from only one item in the TBL network as shown in Figure 6. With the lowest in-degree value, labour law is neglected for the investigations of sustainable development in micro-manufacturing. One of the reasons for this phenomenon is that the needs for labor-intensive tasks in micro-manufacturing sectors have been decreased constantly. The fundamental of micro-manufacturing is now shifting to rely on big data and cloud database, which are the main technological direction of worldwide in this century, and therefore, manufacturers may shift the investment from labor benefits to machinery (Braverman, 1998) and virtual interface (Ghobakhloo, 2018). Another reason for the neglect of labor rights in micro-manufacturing is that feminization of the workforce in global manufacturing industries has been increased dramatically (Hossain et al., 2013). Multinational manufacturing sectors start to relocate their firms to developing countries, where the places that women workers gain an increase in access to industrial jobs. The above global trends in the manufacturing sector further lessen the importance of labor right in the sustainability development for micro-manufacturing.

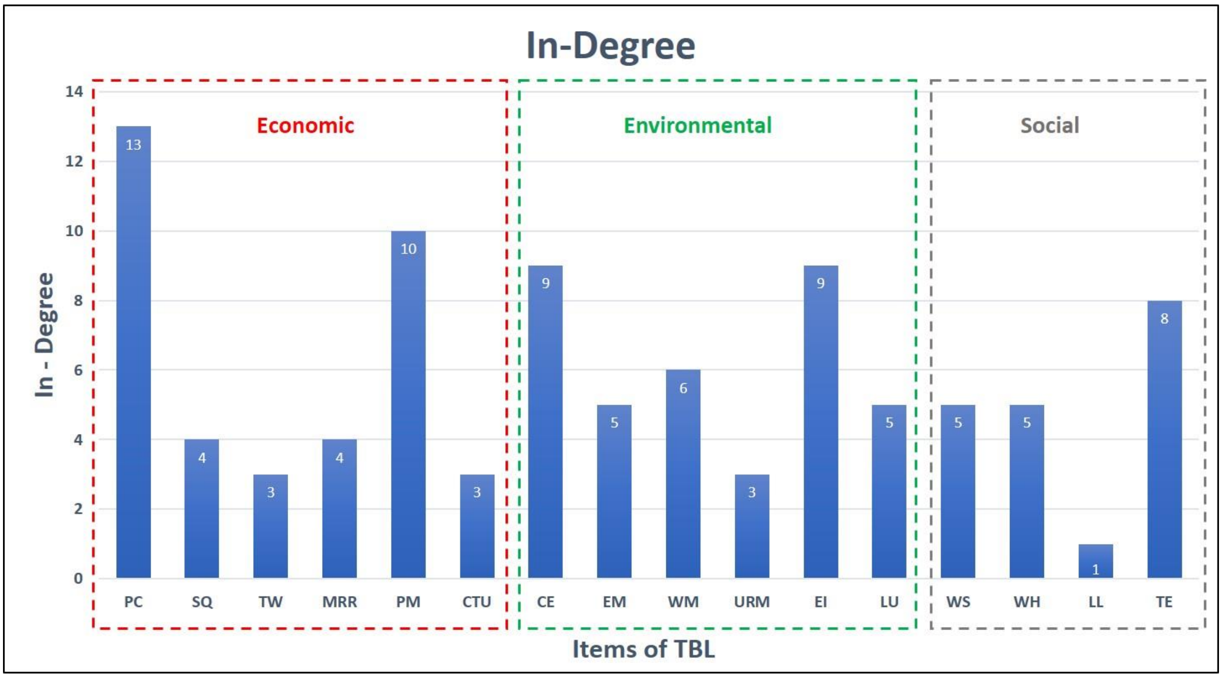

Figure 5. In-degree of items of three dimensions of the TBL network in micro-manufacturing

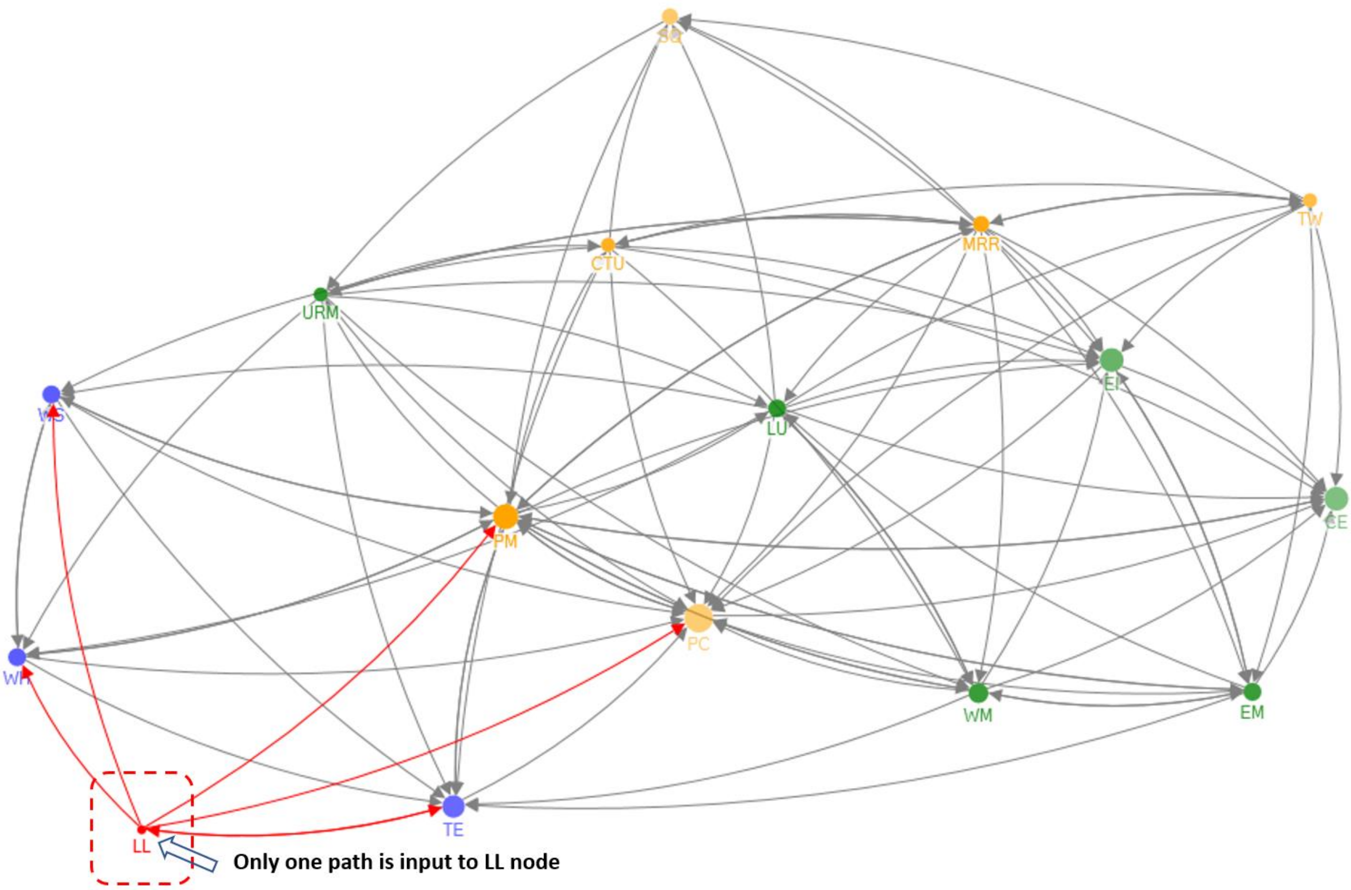

Figure 6. The node labor law only establishes one path at the TBL network

5.3.2 *Out-degree*

Figure 7 shows the values of out-degree of items of TBL framework in sustainable micro-manufacturing. The item with the highest out-degree value is production management, which the value of out-degree is 12. With the interpretation of SNA, production management is treated as the most powerful "influencer" and it provides the influences to the maximum number of items in micro-manufacturing for sustainability development. Being the most significant influencer in the TBL network, a slight change of it would introduce a large degree of variation to other items. For better understanding, take a real case as an example. Colledani et al. (2014) adopted methods and tools to support good production management, which finally offered benefits to wide aspects of production and products such as innovative and integrative product quality, smooth production logistic and maintenance of excellent product design as well as an advanced technological enabler to achieve the good quality of manufactured parts. Good manufacturing management skills enable to increase of the capability of manufacturing staff who have been facing complicated situations, by employing the concept of life cycle thinking, eco-efficiency, green engineering, and clean production (Ageron et al., 2012; Lozano, 2012; Rosen and Kishawy, 2012). The substantial advantages inducing from product management could be contributed to three different dimensions simultaneously, which this phenomenon is successfully revealed by the metric interpretations of SNA.

The item with the lowest value in out-degree is carbon emission. Actually, carbon emission is the result of heavy production activities of micro-manufacturing, which could be treated as the final output at the micro-manufacturing chain. Making changes on the final component at a chain does not exert substantial impacts on the other components/items at the same chain. Therefore, if a reduction of carbon emission is the target for sustainability development in micro-manufacturing, manufacturing sectors should better look at the causes of high carbon emission and execute plans to solve the causes particularly, rather than empirically reduce the amount of carbon emission alone.

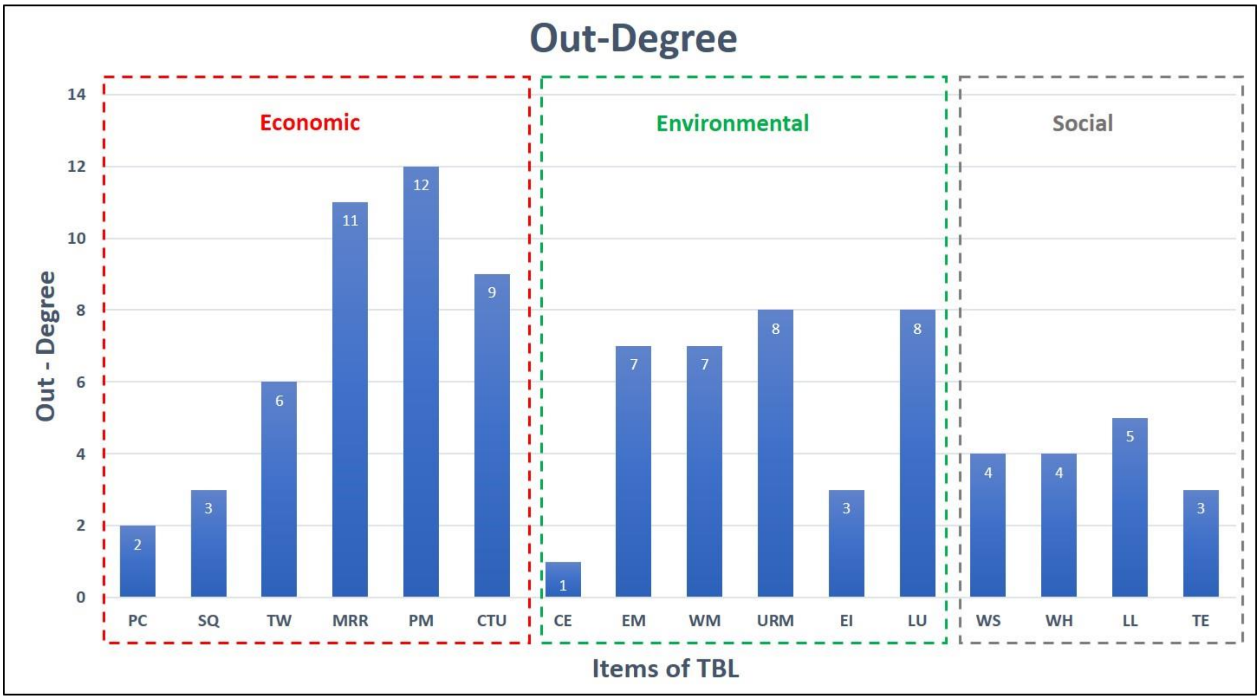

Figure 7. Out-degree of items of three dimensions of TBL network

5.3.3 *Closeness centrality*

Figure 8 shows the value of closeness centrality of items of the TBL network obtained in SNA. The variation of the values in closeness centrality C_c among all items is smaller than that of in-degree and out-degree. No extremely large and zero values of closeness centrality appear. The low variation of the values in closeness centrality C_c of the TBL network states that the effectiveness of the environment activities induced by a particular item is very similar for every item. There is no item able to transfer resources or information to another item using a relatively shorter way, as they all have similar geodesic distances with other nodes. Under the assumption that the item can only transfer the resources to their existing connections, if manufacturing sectors like to use the fruitful results obtaining from the directly linked items for enhancing sustainable development, and integrate with/ transfer them to the environmental activities of other items for solving particular environmental problems, manufacturing sectors should shift to consider to employ other nodes with relatively high betweenness centrality or out-degree to facilitate the processes.

The values of closeness centrality of production management $C_c(PM)$ and production cost $C_c(PC)$ are the largest which are 0.063. Actually, the result of closeness centrality is not surprising when the value of in-degree is considered, in the meantime, the items with the highest values of in-degree are production management and production cost too. There are lots of connections established between production management and production cost with other items. With lots of paths connecting to different items in the TBL network, the relatively shortest paths are easily identified when resources and information are needed to exchange between these two nodes with other nodes. Hansen et al.(2010) suggested a good example to describe the situation for the nodes with relatively high closeness centrality. They mentioned that closeness centrality could be treated as a “distance score”, people with low closeness centrality scores have many miles or rather personal linkages so that they must move with longer paths in order to reach the other people in the network. The item with the lowest closeness centrality is labour law, which value is 0.4. Actually, in-degree of labor law is only 1, which means that labour law only established a path with one item, which the result of closeness centrality is consistent with that of in-degree – the relatively low attention on the labour law in the sustainable development of micro-manufacturing currently.

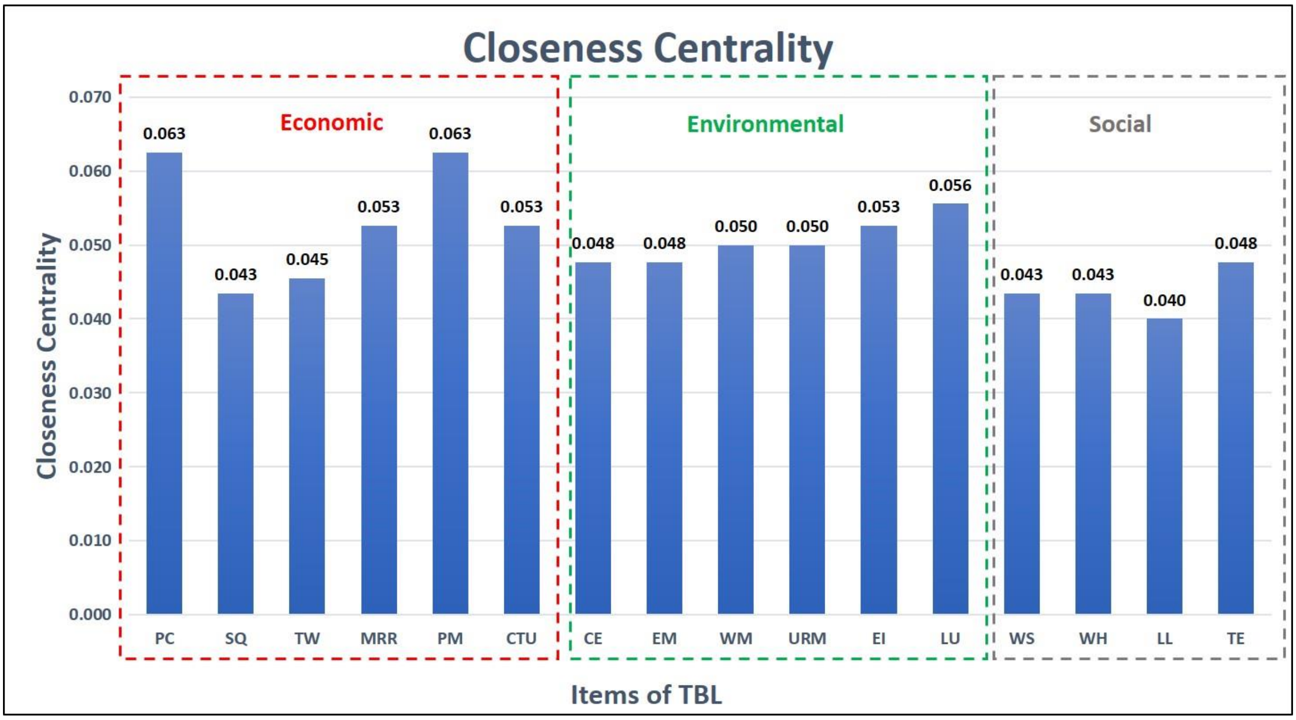

Figure 8. Closeness centrality C_C of items of three dimensions of TBL network

5.3.4 *Betweenness centrality*

In SNA, the distance between two non-adjacent nodes in SNA is simply expressed by the number of edges generated with neighbor-to-neighbor hops from one node to another node. The shortest path between two nodes is measured by the smallest number of edges generated by neighbor-to-neighbor hops. Betweenness centrality is a measure of how often a node lies on the shortest path between two other nodes (Hansen et al., 2010). This is similar to the concept of a bridge linking different nodes in the network. The value of betweenness centrality is a "bridge" score (Hansen et al., 2010), which is an expression of how the level of disruption to the connections between other nodes in a network when a particular node is drawn out from that network. "Brokering" is often used in describing the concept of betweenness centrality. Refer to Figure 9, production management and production cost obtain the highest values of betweenness centrality, which the values of $C_B(PM)$ and $C_B(PC)$ are 19.26 and 19.11 respectively. With the highest betweenness centrality, they act as the roles of the bridge to connect most of the nodes in the network. If these two items are removed from the TBL network, the other items in the TBL network would have difficulties in connections. For example, if production cost and production management are neglected in the sustainable development of micro-manufacturing, the final goal may not be easily achieved by the initial action, as the bridges of sustainable development are broken in this case. Evidence of production cost as an important linkage of other items of TBL framework are shown by literature. Literature showed lots of case studies about the indirect effects of production cost on the overall performance of sustainability development using TBL. Hollos et al. (2012) investigated sustainable suppliers using the survey of Western European firms, and they found that sustainable supplier co-ordinations did not directly enhance the economic performance of firms, on the contrary, it impacted the social and green behaviors of firms. Therefore, manufacturing sectors actually could employ the production expense as a tool to connect different items in TBL and finally achieve sustainable goals.

Conceptually, missing the nodes with the highest betweenness in the network would cause a situation similar to "a structural hole at the bridge". If two or more nodes are unable to connect because of the missing nodes, the phenomenon is treated as a gap needing to be filled. Therefore, if the network composes of the items relating to technology, an existing ignorance of high betweenness node would be treated as the existence of a technological gap, it would be the chance for manufacturing sectors to achieve technological breakthrough through posing actions relating that high betweenness node. In the sustainability development of micro-manufacturing, refer to the results of SNA, the areas of production cost and production management would be treated as the chances for manufacturing sectors to make the breakthrough. Manufacturing sectors should recognize these gaps and reallocate the resources to grasp these opportunities for achieving sustainable development.

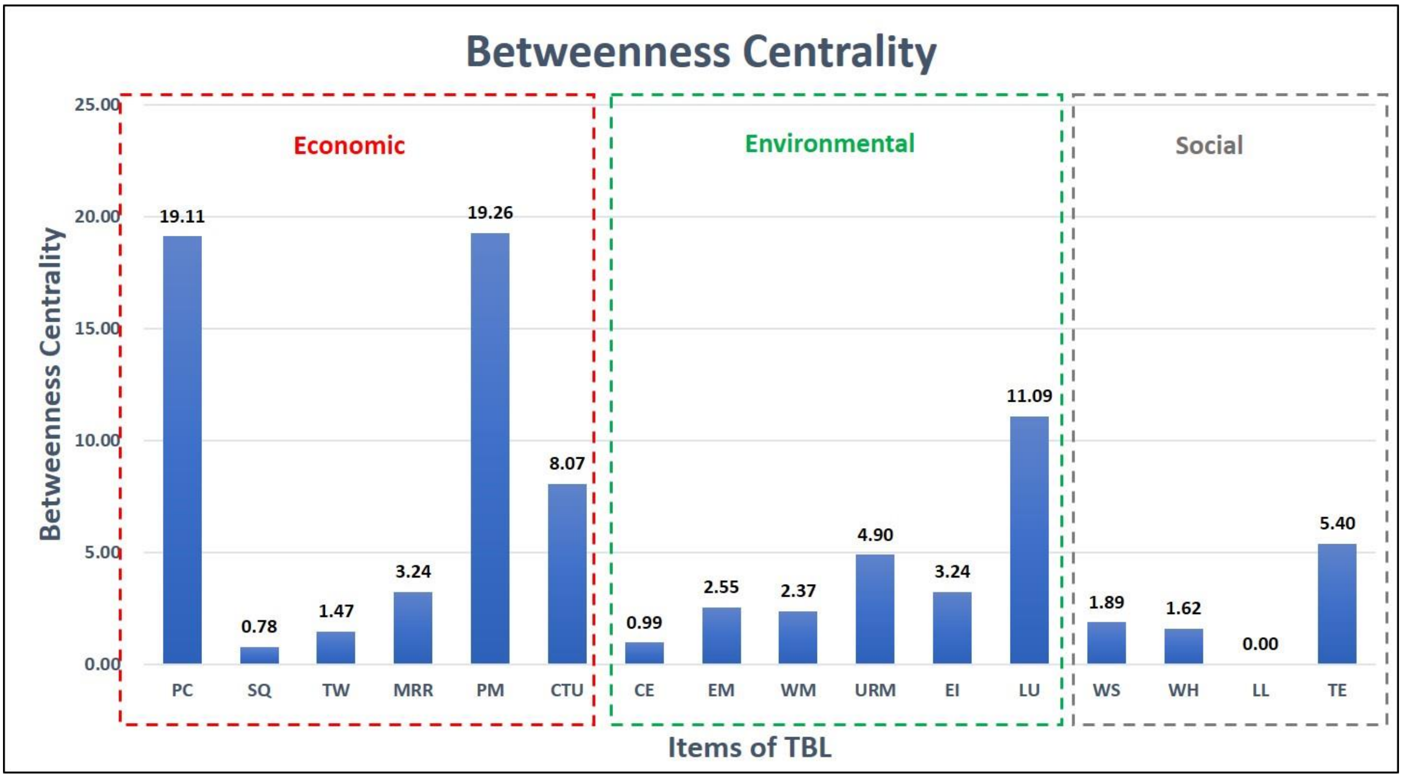

Figure 9. Betweenness centrality C_B of items of three dimensions of TBL network

5.3.5 Overall analysis on the metrics of items of the TBL network

In order to read the overall performances of the items in the TBL network, the rankings of different metrics for every item are shown in Figure 10. The rankings of items in the social dimension are comparably low (given to the higher value of ranking in Figure 10) among the items in other dimensions. On the contrary, the items in the economic dimension receive high rankings for all metrics including in-degree, out-degree, betweenness centrality and closeness centrality. The metrics of SNA reveal that the environmental activities arising from the social dimension in micro-manufacturing are highly isolated from the items of other dimensions, the environmental activities of social dimension are seldomly received from or place influences on the environmental activities of the other dimensions, with rarely mentioning if ethical and social topics for the TBL (Carter and Jennings, 2004). Actually, scholars expressed opinions that the role played by the social dimension has been rarely equal to the environmental and economic dimensions (McKenzie, 2004; Yip and To, 2021). The Global Reporting Initiative has reported that the social performance of sustainable development is delivered uncommonly and inconsistently across organizations.

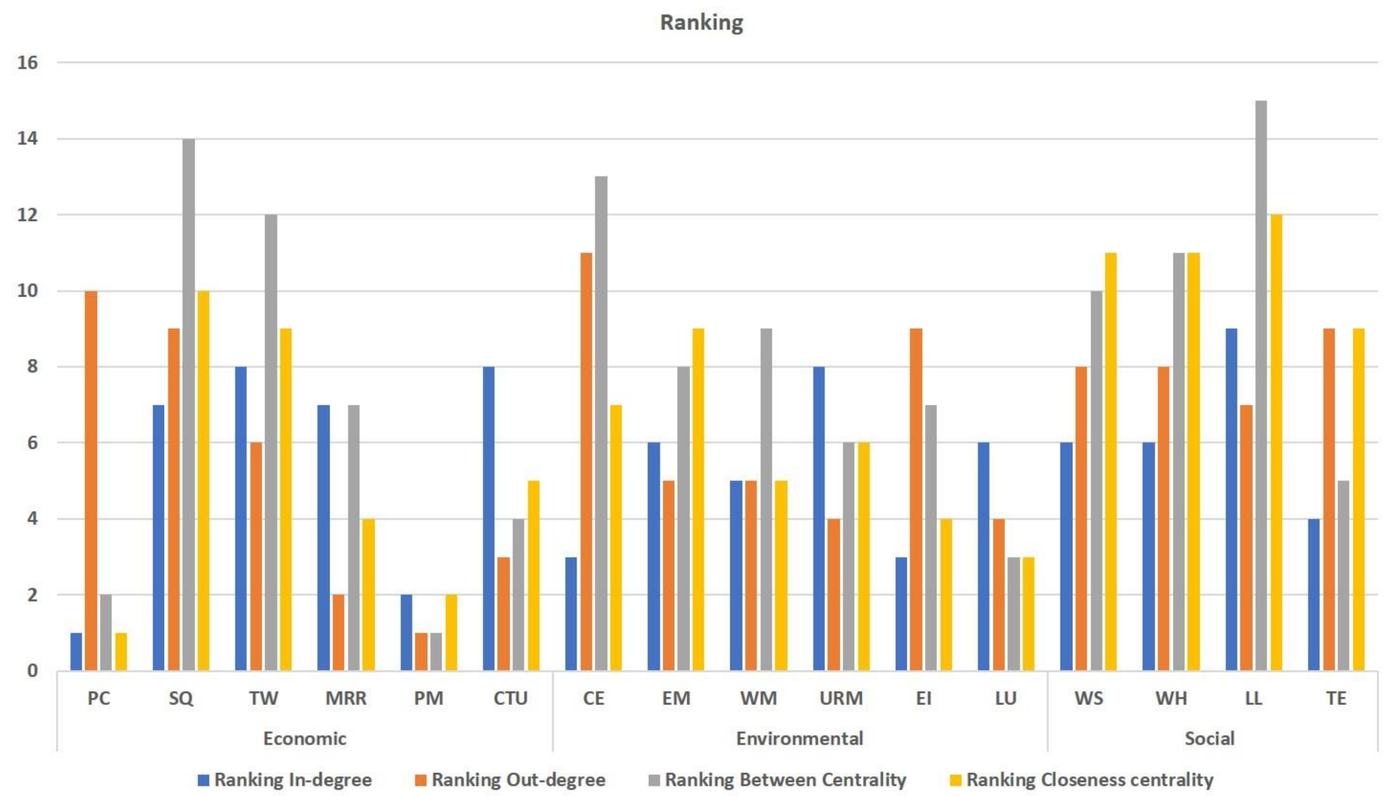

Figure 10. Metrics of all items of three dimensions of TBL network for micro-manufacturing

5.4 Visualization analysis of TBL network

Visualization of a network constructed by SNA enables to provide a general idea of the overall inter-relationship of the network, supporting to interpret of the physical meanings of the nodes at the corresponding positions of the network. In this section, the TBL network was reconstructed by a force-directed graph drawing layout called the Fruchterman-Reingold algorithm for visual analysis, which the network graph is shown in Figure 11. Theoretically, springs like attractive forces based on Hooke's law are the origins of attracting node pairs towards each other, at the same time, repulsive forces following Coulomb's law are employed to separate the node pairs. The absolute values of the forces in the Fruchterman-Reingold algorithm are denoted as:

$$\mathrm{f}_{attractive}(\mathrm{u},\mathrm{v}) = k^2 / d\,(u,v) \quad (4)$$

$$\mathrm{f}_{replusive}(\mathrm{u},\mathrm{v}) = d\,(u,v)^2 / k \quad (5)$$

where $\mathrm{f}_{\mathrm{attractive}}$ and $\mathrm{f}_{\mathrm{replusive}}$ are the attractive and repulsive forces respectively. The directions of the forces are obtained in terms of two-dimensional vectors u and v. k is a constant describing the distance between two connected nodes at the equilibrium state.

Referring to Figure 11, the graph is divided into three parts based on the classification of three dimensions in TBL. The nodes, production cost, production management and labor law, would be the focuses of discussions here as their metrics are relatively high/low, which comprehensive knowledge can be demonstrated by examining their metrics. With the nature of the layout algorithm, Fruchterman-Reingold algorithm, the distances between each node are based on the attractive and repulsive forces with the function of the geodesic distance of edges at the equilibrium state.

For the node of production cost, it locates at the edge of the economic group with a relatively long distance to the social dimension and a short distance to the environmental dimension. This position means the nature of environmental activities concerning production cost is related to the contents of the environment dimension, rather than that of the social dimension. Similar interpretations could be applied to production management and labor law. The location of production management in the TBL network is nearer to the social dimension but farther from the environmental dimension, which means that the environmental activities arising from production management in micro-manufacturing mostly related to the social dimension. For labor law, although it has the lowest in-degree and betweenness centrality, it locates at the edges near to the environment and economic dimensions. However, as there are extremely few established connections between labor law and items in the other two dimensions, the resources inducing from the labor law could not be directly transferred and benefited to the other two dimensions for the sustainability development.

The other valuable nodes for investigations are “surface quality”, “tool wear” and “work health”, their positions at the network graph are “corner” at one or two dimensions. For the nodes of work health and tool wear, they locate at the corner positions of two dimensions in the network graph, they have a close relationship with two dimensions but separate from another dimension. Manufacturing sectors should move these nodes toward the remaining dimension in order to get the balance for the three dimensions of TBL. Actually, these two nodes provide the chance for manufacturing sectors to easily grasp the benefits from the remoted dimension through effective actions. For the node of surface quality locating at the comer position of one dimension, this node is simply far away from all other two dimensions. Although the metric score of it is not extremely low, the current position of it causes the difficulties of building up paths originating from it, i.e., manufacturing sectors need to devote considerable efforts to overcome the forces inserting from the current TBL network, for moving the node to the desired position in the network before executing the environmental plans for better resource allocations.

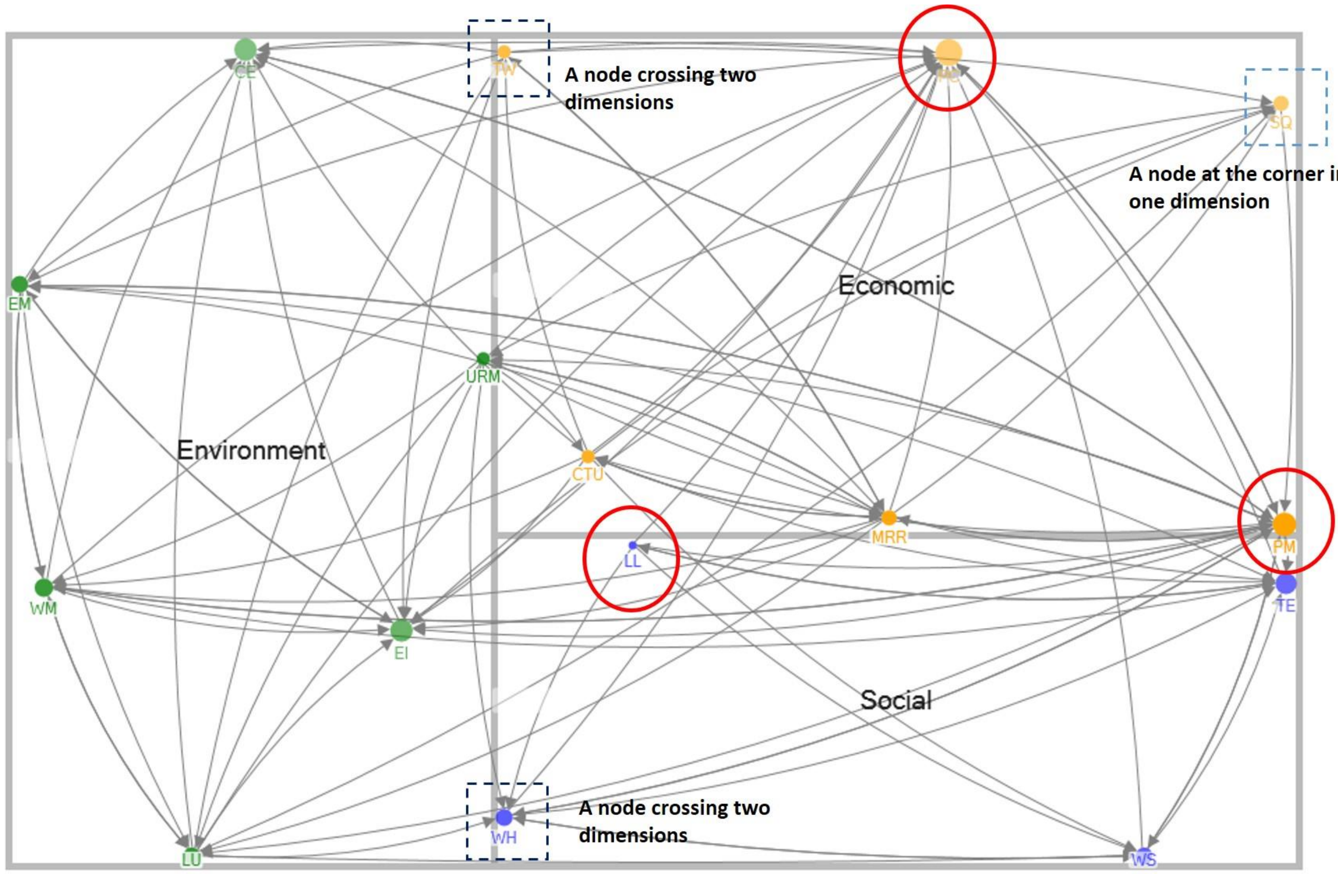

Figure 11. the TBL network constructed by Fruchterman-Reingold algorithm

6 Conclusion

Due to the high complexities of inter-relationships and unclear interpretation of items in the current TBL framework, the difficulties of executing sustainable developments in micro-manufacturing are further intensified. In this study, SNA is applied for identifying the clear inter-relationships between items and giving precise definitions of items in the TBL framework. Micro-manufacturing sectors and researchers enable to efficiently plan for sustainable micro-manufacturing strategies referring to the findings in this study which benefit our environment. With the obtained metrics of items and the visual analysis of the entire TBL network constructed by SNA, the following major findings are worth noting:

1. The numbers of the reciprocated edge ratio and the reciprocated vertex pair ratio of the social dimension in the TBL network constructed by SNA are relatively higher than that of the other two dimensions of

TBL, they demonstrated that the level of influences inducing from items to items at the same dimension in TBL is the largest for the social dimension.

2. The relatively strong individual state of the social dimension in TBL of sustainable micro-manufacturing is revealed by SNA analysis. The environmental activities of the social dimension are rarely supported by or benefited to the other two dimensions in micro-manufacturing.
3. For the result of in-degree of SNA, production cost obtained the highest value of in-degree. It explained that production cost in micro-manufacturing is affected by the highest number of environmental activities from the items of the other dimensions. Adjustments of environmental strategies on the other items of TBL for the sustainability development in micro-manufacturing will consequently influence production cost. For the result of out-degree of SNA, production management is also the most significant influencer in the TBL network. Therefore, the benefits inducing from product management could be contributed to three dimensions simultaneously. For the result of closeness centrality, the items of production management and production cost are the largest values. the relatively shortest paths are obtained from these two items when resources are needed to exchange between these two nodes with other nodes. Production cost and production management are the nodes with the values of highest betweenness centrality. Therefore, environmental activities arising from these two items could be planned intelligently in order to effectively achieve the targeted results.
4. Visual analysis of the TBL network showed the nodes of labor law, production cost and production management are at the edge comprising two dimensions. Therefore, they could be treated as the chances for manufacturing sectors to establish paths originating from them for enhancing sustainable micro-manufacturing.

The study employs a novel approach to analyze sustainable micro-manufacturing focusing on the TBL concept through network-based approaches. It does not only provides the literature references as a case study but also offers a unique approach to describe the environmental impacts from the different items initiated by micro-manufacturing. This study shows the environmental impacts of sustainable micro-manufacturing focusing on the TBL concept with wide viewing points from manufacturing sectors and academia. It benefits the areas of micro-manufacturing as well as engineering and technology, supporting the related parties to make decisions and undertake management activities.

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