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A spatio-temporal product lifecycle network representation

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Abstract. Product lifecycle is a complex network with large supply chains from multiple organisations. Lifecycle assessment of products of organisations with globally dispersed manufacturing supply chains and international market involves various spatial and temporal constraints. Even though organisations have data of their global supply chains, data is typically stored textually as spreadsheets, or visually as process flow charts. Visual representation of this large data using flow charts makes it complex and difficult to read and interpret. A decluttered, simplified product lifecycle data representation method is presented in this paper, which is developed for use alongside an LCA tool.

Keywords: Spatio-temporal network · Product lifecycle mapping · Global manufacturing.

1 Globally Dispersed Product Lifecycle

Geographically dispersed manufacturing makes the lifecycle of a product from an organisation a large network with global supply chains. Companies build or acquire manufacturing facilities in different countries based on strategic business reasons. For example, General Electric Aviation headquartered in Ohio, USA, opened a component manufacturing, service, support and sales centre in 2010 in Singapore to cater to the Asia-Pacific region as well as the international market [1]. Original Equipment Manufacturers (OEM) source around 80% of the value of the final manufactured product from outside their companies [2]. Apple iPhone manufacturing involves nine different companies from the USA, Germany, China, Korea, Japan, and Germany [3]. Hence, understanding the lifecycle of a company's product with globally dispersed manufacturing supply chain, market and service networks, involves spatial and temporal data. Decision to select manufacturing locations by companies are based on specification satisfaction, quality, cost of manufacturing, shipping costs and time, and process scheduling. Individuals—employees of companies with global manufacturing networks, component manufacturers, and material suppliers—do not have an understanding of where they stand, and how crucial the role they play is with respect to the product lifecycle network. This is not due to non-availability of information; but rather due to the complexity of information in the way it is currently stored. The following quote from Lewis E Platt, former CEO of HP illustrates this difficulty. “If HP knew what HP knows, we would be three times as profitable” [4].

Even though organisations have record of their global supply chains, these are most often stored textually in the form of spreadsheets, or visually as process flow charts. Commercially available PLM tools (e.g. Enovia, Teamcentre) store these data in the form of textual records attributed to product geometry. LCA software (e.g. SimaPro) do not capture company data, but prompts the tool user to select equivalent processes from commercially available LCA databases (e.g, Eco-invent) and displays the environmental impact values of the product. Neither PLM nor LCA tools provide a complete understanding of the product lifecycle network. A product’s lifecycle with global manufacturing, distribution, use, re-use and disposal network involves geographically dispersed processes across time zones and lifecycle phases. Hence it involves spatial and temporal information of these processes. A spatio-temporal product lifecycle representation method is presented in this paper, which is developed for use alongside an LCA tool.

2 Information Visualisation in Product Lifecycle

Visualisation is the process or activity by which non-visual information is converted to a visual form [5-8]. Companies use Gantt charts and flow charts to understand process sequences and identify critical processes for project scheduling and planning purposes. These diagrams capture the temporal and sequential dependencies of processes involved. The spatial aspects are not reflected in Gantt or flow chart diagrams. For example, Gantt charts would look the same whether two sequential processes were to take place in the same location or in two different continents, as long as the duration of these processes remained the same. Flow charts do not represent actual process durations involved unlike in Gantt charts, and do not show spatial information. A process flow chart would hence appear the same, irrespective of the variations in process durations, and whether individual processes took place across the globe or in the same plant. It merely shows the sequence or processes. Such oversimplification in visualisation leaves out essential information needed for decision making by an individual. One is unable to evaluate the real world reasons for supply chain disruptions or delays - for example, a natural calamity in the location where components are manufactured; a political scenario which led to closure of a factory; an increase in cost due to local economic conditions; an environmental law which prevented the functioning of a manufacturing plant due to its emissions, etc. Such aspects involving legislations, and demand for sustainable activities are increasing the complexity of product design [9-11]. Companies in high technology industries face challenges due to product complexity and globally dispersed product design activities [9, 12].

Geographic Information System (GIS) tools in logistics (E.g. ArcGIS) map supply chain information on a two-dimensional map. An example of how such a mapping would look for the Boeing 747-8’s manufacturing network is shown in Figure 1. More information layers can be added on GIS tools over the 2D base map which would be displayed in the form of text or tables. GIS tools do not capture temporal dimensions of individual processes and their sequences like in Gantt and flow charts. However, they capture time indirectly through real time tracking for shipments.

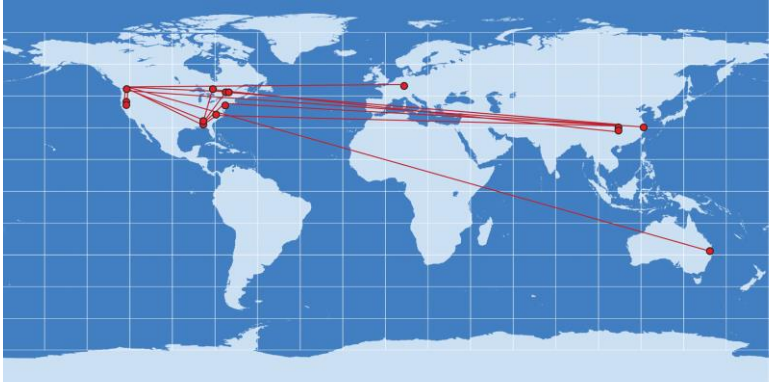

Fig. 1. Manufacturing network of Boeing 747-8[1].

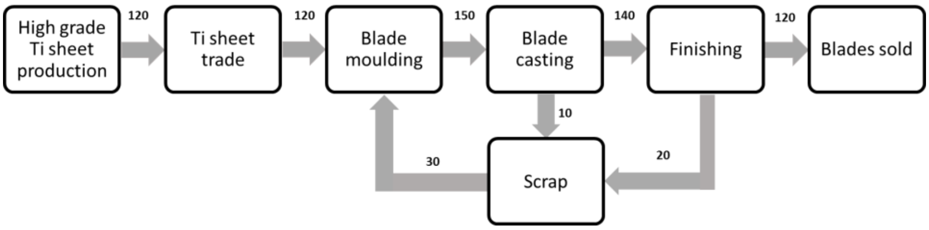

Fig. 2. Material flow of Titanium blade manufacturing process for Rolls-Royce Trent 1000 engine[1]

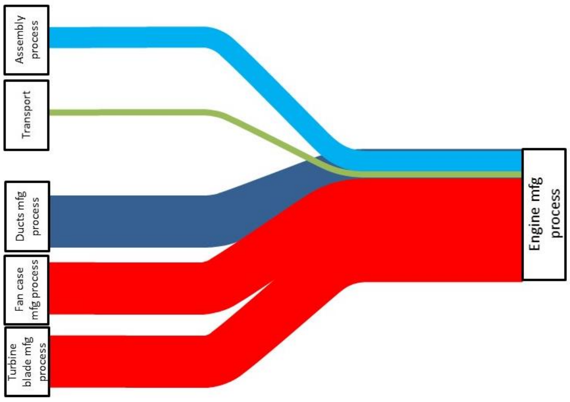

Fig. 3. Sankey diagram showing LCA results of manufacturing processes for Rolls-Royce Trent 1000 engine[1]

The Material Flow Analysis (MFA) method, which is based on material flows and mass balance of a system boundary, uses flow charts with stock quantities alongside

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[1] Data sourced from a video documentary, and online sources [13]. Assumptions of locations and values are made for representation purposes.

for visual representation of data. An example of Titanium fan blade manufacturing process for Rolls-Royce Trent 1000 engines used in Boeing 787 Dreamliner is shown in Figure 2. This diagram captures the process sequence along with stock quantities of inputs and outputs. The MFA flowchart does not provide information on locations at which the processes took place, locations from where the inputs were sourced, locations where the waste generated were disposed, and locations where the recycled stocks were used. MFA flowcharts do not provide temporal information of processes as well. Sankey diagrams and bar charts are used by LCA tools (for e.g. SimaPro) to show the environmental impact and emission values. An example of Rolls-Royce Trent 1000 engine manufacturing process is depicted in a Sankey diagram in Figure 3. The Sankey diagram shows process-wise environmental impacts; the thicker the line, the higher the impacts are, and vice versa. This depiction is end-product focussed and does not show the spatial or temporal dependencies of the processes involved.

Other visual representations used in manufacturing and production planning and other spatio-temporal representations are reviewed elsewhere [14]. Most of these representations become complex and cluttered while representing large datasets of product lifecycle information. GIS based tools when used for product lifecycle data, display many criss-crossing lines connecting locations in maps where the user cannot comprehend the entire network. MFA flowcharts if drawn for entire product lifecycle, will have many processes with arrows in different directions and stock quantities. The flowchart size will be large and a user can get confused while following the arrows going back and forth. Sankey diagram for LCA results of a product lifecycle will have large number of processes with criss-crossing lines of varying thicknesses and colours. A decluttered and simplified product lifecycle data representation method with spatial and temporal information is necessary for better understanding and decision making involved with global supply chain networks. One such representation is proposed in this paper, which is developed for use in an LCA tool.

3 Proposed Space-Time Network Method

The need for a new visual representation arose when the data of geographically dispersed manufacturing, lifecycle processes, inventories, and environmental impacts associated with them had to be analysed to aid decision making, while using an LCA tool under development for a sponsored project from industry. Potential first tier end users of the tool include design engineers, department heads, project managers, R&D personnel and top-management. Second tier end users of the LCA tool would be component manufacturers, suppliers, partnering companies for sub-assembly manufacturing. The LCA results would be used for discussions with end users in order to optimize a product's global supply chain network for reducing environmental impacts. These results would also be useful in discussions with third tier users, e.g. factory floor employees. Since geographically dispersed supply chain involves working with people from different countries, the challenges involved with this are: a) the data and results must be easy to comprehend for people from varying educational backgrounds; b) it should be readable irrespective of linguistic barriers across regions; c) compatibility of the data representation method for use in print form at locations or situations where there are no computers or devices to display the data, such as small-scale manufacturing units in developing countries.

The information layers needed for decision-making were arrived at based on the information the three tiers of users would need and how the challenges described above can be overcome. The information needed are as follows:

a) Lifecycle processes and their sequence: A lifecycle process sequence is defined here as a set of all discrete processes which should take place in a desired sequence in order to manufacture, use, service, or dispose the product. It is a superset of processes involved in all lifecycle phases—material, manufacturing, assembly, transport, use, re-use/disposal.

b) Spatial and temporal information of lifecycle processes: Spatial information includes locations of lifecycle processes—city and country names, or geographic co-ordinates. Temporal information includes durations of each process.

c) Inputs and Outputs for each lifecycle process: Inputs and outputs include material, energy and information, e.g. material resources, products, electricity, fuels and lubricants.

d) Equipment and People: Equipment are machinery involved in order to carry out a process. For e.g., large machines, computing, sensing and testing devices, and transport devices such as trolleys, cranes, and automobiles.

e) LCA results: LCA results can be in the form of single point values or ranges for each process involved.

A new representation named Space-Time Network (STN) Method was designed based on the objectives and the information to be represented. Figure 4 describes the basic elements of STN method. The STN method uses an inverted graph to plot space along the x-axis, and time along the inverted y-axis. The unit of x-axis are the geographic co-ordinates of the locations involved. Every unique geographic co-ordinate value is allotted one unit position in the x-axis. The order of placing the locations is based on the West to East -North to South Rule (WENS Rule) explained below:

1. Successive positions in the x-axis from left to right in the STN graph will be allotted in the order of appearance of the longitude values from West to East in a world map.
2. If two or more geographic co-ordinates have the same longitude value, the successive positions in the x-axis from left to right will be allotted in the order of appearance of latitude values from North to South in a world map.

This rule makes it easier for anyone to mark the x-axis positions by just looking at a commonly used world map. A world map is used along with STN graph to map the locations from the 2D maps to the x-axis unit positions of STN graph. The example in Figure 6 illustrates this. The WENS Rule eliminates the clutter of criss-crossing lines as observed in GIS based tools (see Figure 1). The unit of time in STN graph can vary depending on the unit of process durations for each product lifecycle. The unit can be in seconds for a product with a shorter production time and lifecycle; it can be in days or months for products with longer production time and lifecycle. Absolute time can be used as well to represent the durations.

Each process is represented in an STN graph as a straight line with its x-axis representing the location of the process (Figure 4). The y-axis or the length of the line signifies the duration of the process. The diagonal lines in Figure 4 are connectors.

Global connectors (Global In and Global Out) and local connectors (Local In and Local Out) are used to link process chains and material flows, between two locations and the same location respectively. The connectors are drawn as notations, and it is represented using a diagonal line of uniform length and angle with two nodes (start and end). The orientation of the connectors are different depending on the type of connector. There are four connector types:

1. *Global In*, G_{in}: a connector to the left drawn at the start node of a process. G_{in} denotes, the process to which it is connected receives input material sourced from another location.
2. *Global Out,* G_{out}: a connector to the left drawn at the end node of a process. G_{out} denotes, the process to which it is connected has an output to be shipped to another location.
3. *Local In,* L_{in}: a connector to the right drawn at the start node of a process. L_{in} denotes, the process to which it is connected receives an input sourced from the same location.
4. *Local Out,* L_{out}: a connector to the right drawn at the end node of a process. L_{out} denotes, the process to which it is connected has an output which is either locally discarded, or goes for recycling.

Different combinations of input-output scenarios exist in a product lifecycle and supply chain. Every possible scenario can be depicted using these four connectors as shown in Figure 5. What each of these scenarios signify is explained in Table 1. The connectors eliminate the issue of clutter due to criss-crossing of lines in GIS based or any map based representations. The connectors enable the network to expand as more information becomes available, without having to redraw the rest of the graph. The equipment and people involved are shown, using graphic symbols of gear and human respectively, next to each process. The count of the symbols denote the equipment and people count in each process. Transportation involved in G_{in} and G_{out} is shown using a truck symbol next to these connectors.

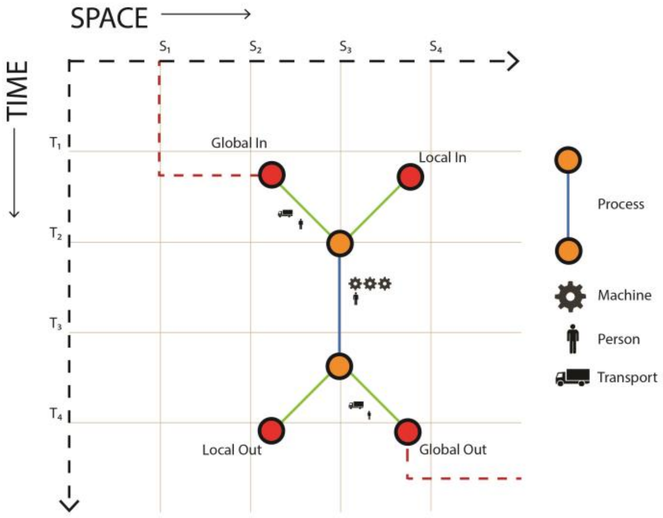

Fig. 4. Basic elements of a Space-Time Network Graph

The logic of plotting an STN graph is described below:

Here, S denotes *space*; t, *time*; P, *process*; Out, *output*; Inp, *input*.

1. S_i (t) is a location point in the space-time co-ordinate at a given point of time. The co-ordinate values of the point S_i (t) will be (S_i, t_i), where i = 1, 2, 3…
2. A process, P_{ij} is defined by a pair of 2 points (S_i, t_i) and (S_j, t_j) where $t_j > t_i$; i= 1, 2, 3…; j= 1, 2, 3…
3. A G_{out} or G_{in} is a process, P_{ij}, defined by a set of 2 points, (S_i, t_i) and (S_j, t_j); where $t_j > t_i$; $S_i \neq S_j$; i= 1, 2, 3…; j= 1, 2, 3…
4. An L_{in} or L_{out} is a process, P_{ij} defined by a set of Input-Output values of P_{ij} and its succeeding process P_{jk} such that $\{Out\ P_{ij}\} \neq \{Inp\ P_{jk}\}$; where $S_{ij}=S_{jk}$; $t_k > t_j > t_i$; i= 1, 2, 3…; j= 1, 2, 3…; k=1,2,3,…

The basic elements of the STN graph have been described in this section. The next section explains how the STN graph depicting LCA results can be plotted, using an example of product supply chain and lifecycle network.

3.1 Example of Boeing 747-8 using STN Method

An example of Boeing 747-8's supply chain network, involving processes from the life cycle phases of material, manufacturing, assembly and transport, is demonstrated using the STN method. Data for this was accumulated by transcribing documentary videos of Boeing 747-8 and GE engine manufacturing [15, 16], and from information available in company websites [17]. The data displayed is not an accurate representation of The Boeing Company's actual supply chain network. Assumptions have been made for demonstration purposes of the STN method. The Boeing 747-8 has 6 million parts, most of which arrive just-in time [15]. The major subassemblies for the Boeing 747-8 are the GE Engines GE nx-2B, wing elements, landing gear and structural elements. All of these are sourced from different plants and locations. The major components for GE nx-2B engines are turbine blades, fan cases and fan blades, which are sourced from different companies or manufactured at plants at different locations. The aircraft assembly, engine manufacturing, turbine blade, fan blade and fan case manufacturing for engine assembly are demonstrated in this example using the STN graph (see Figure 6).

The range of impact values from LCA results are categorised into a colour spectrum (see Figure 6, right side). The LCA value for each process is checked against this colour spectrum and the corresponding colours are used for the process lines. The overall impact of the lifecycle network is shown on the right side (see Figure 6, below colour spectrum). The overall impact is shown in a circle, with the impact value depicted using the corresponding colour from the spectrum. The lifecycle phase-wise aggregated impact values are shown on the right side in a colour coded circle depicting its value, with a red line depicting the end of each phase. Each lifecycle phase is demarcated with respect to the product for which the lifecycle is evaluated, which in this example is the Boeing 747-8 aircraft. Space-wise aggregation of LCA results are shown using colour coded circles (as per the spectrum) at the end of each x co-ordinate position, which denotes the corresponding locations.

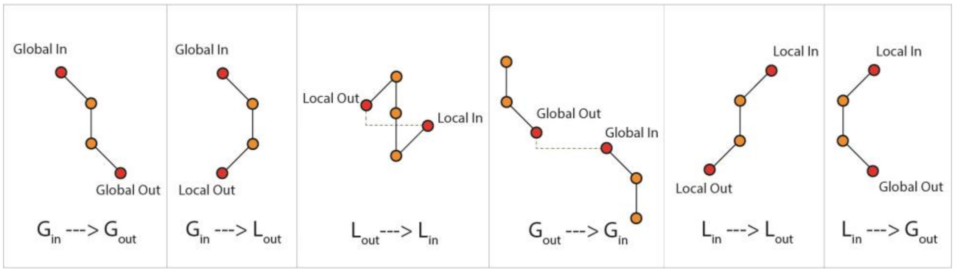

Fig. 5. Possible combinations of input-output scenarios represented using connectors in STN graph

Table 1. Meaning of connector combinations with respect to input-output scenarios

Connector combinations	Meaning
G_{in} - G_{out}	Receiving raw materials/products/finished goods from another location and shipping the finished product to another location
G_{in} - L_{out}	Products/Materials from other locations received as an input and output disposed locally
L_{out} - L_{in}	An output is recycled and is reused by receiving it as an input to another process
G_{out} – G_{in}	Output in the form of raw materials/products/finished goods are shipped to another location where it is an input to a process
L_{in} - L_{out}	Locally sourced material is used as an input to a process and its output is locally disposed or recycled
L_{in} - G_{out}	Locally sourced material is used as an input to a process and its output is shipped to another location

4 Advantages and limitations of STN method

A manufacturing plant has machines running continuously and simultaneously, producing parts and products in batches. At every instance of time, different batches of products are at varying degrees of completion. The STN method, by focussing on one manufacturing lot, produces a clear picture of a product’s lifecycle network and its dependencies across different locations and processes. From Figure 6, one could distinguish 5 different chains showing processes taking place in 5 locations. The STN method also carries the good aspects of the commonly used graphical representations which are: the sequence from material flow analysis, geographic tagging from GIS, use of colours in Sankey diagrams for LCA results, and temporal information and process dependencies from Gantt charts. The material flow is captured, without having to show the quantities, by use of G_{in}, G_{out}, L_{in} and L_{out}. The colour coding of processes, and space-wise and lifecycle phase-wise aggregation of LCA results enable users to locate the individual process, or location, or the life-cycle phase, which contribute to higher environmental impacts. With this knowledge, decision makers have better chance to optimise the network effectively for reducing the environmental

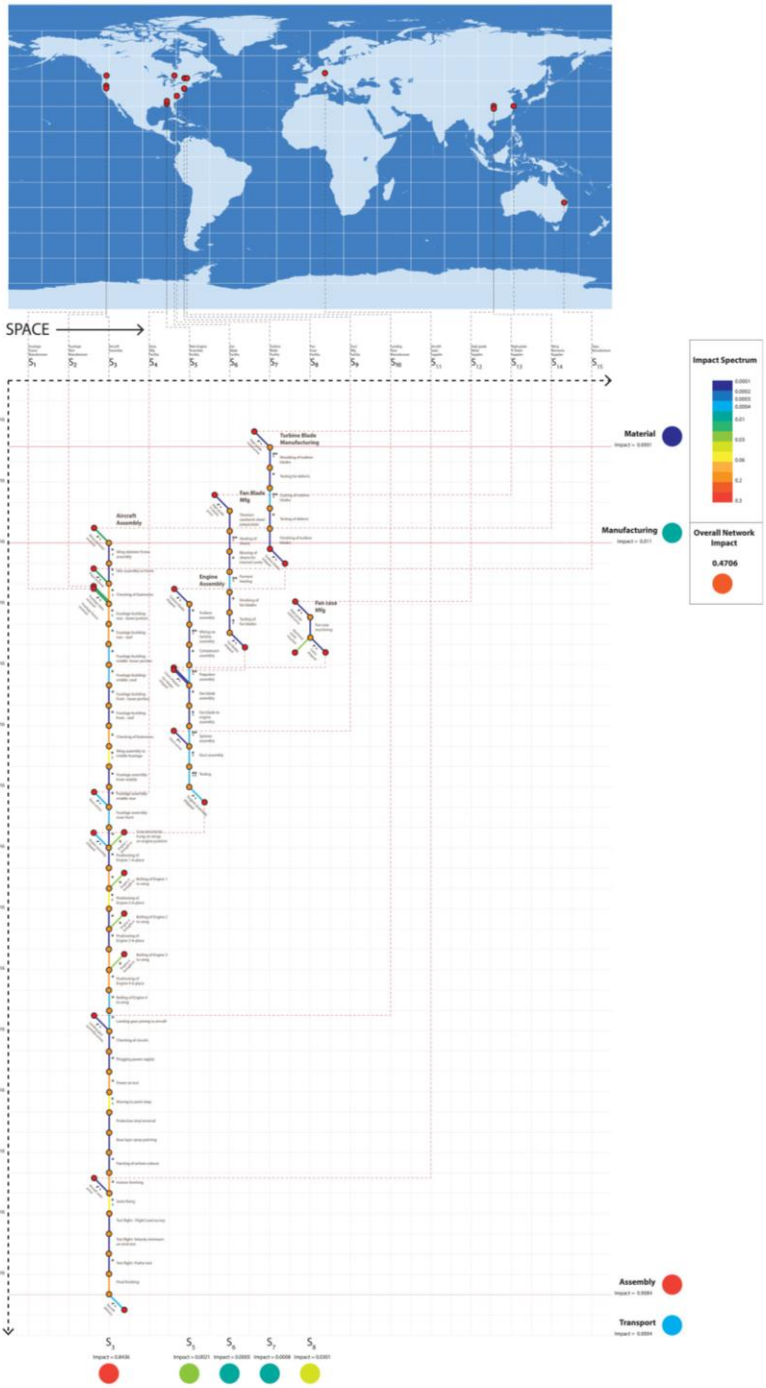

Fig. 6. Space-Time Network representation of Boeing 747-8. (Impact values are only for indicative purposes). Figure 7 shows an enlarged image of a portion of this diagram.

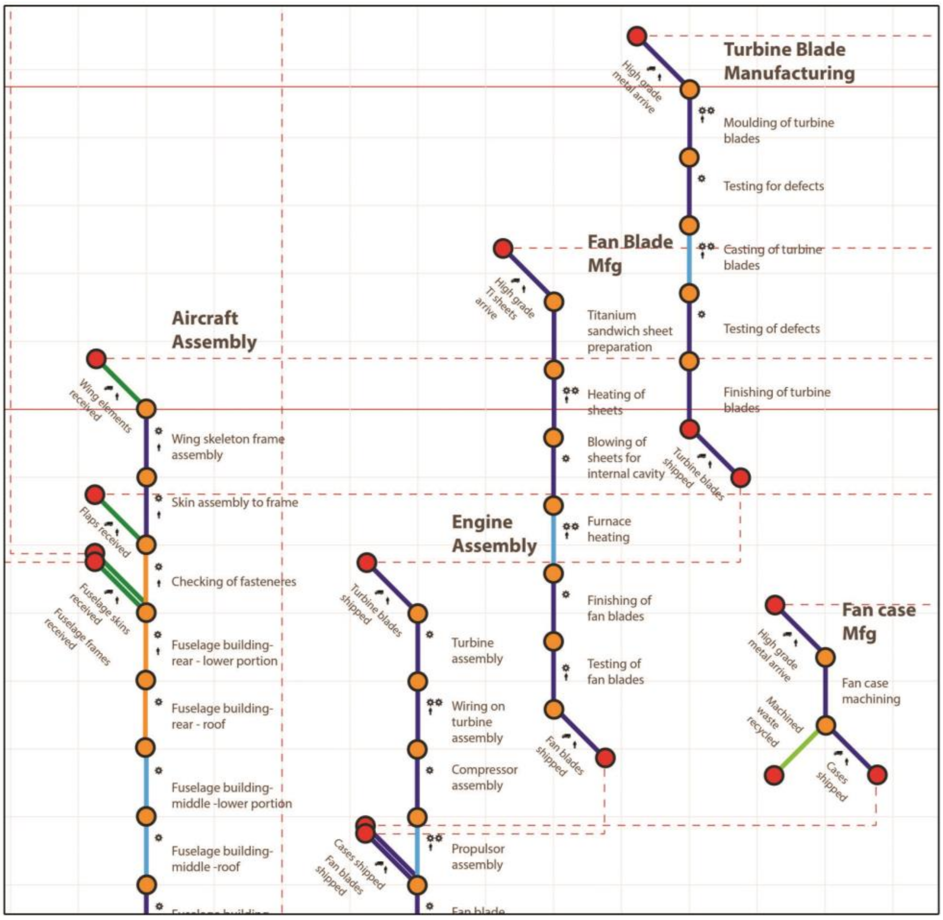

Fig. 7. Enlarged portion of the STN representation of Boeing 747-8 example in Figure 6.

impacts. Alternative lifecycle networks can be compared easily using this method. Two networks can be compared, or the same network can be optimised for reducing environmental impacts, till the desired values are achieved.

The STN graph can be used for an entire product lifecycle or for individual lifecycle phases. It can also be drawn for an individual factory, where each zone is represented by different points in the x-axis. STN graph captures the real scenario when it comes to recycle-reuse-disposal phase. In most representations in PLM and LCA, re-cycle and re-use phases are depicted as a loop connecting the manufacturing process. In reality and in STN method, the L_{out} (discarded outputs) join as L_{in} (recycled inputs in this case) at the next point in space and time where those processes that take them as input actually occurs.

The STN method supports addition of more supply chain and life cycle data into the network as more information becomes available. The whole product lifecycle can be built in a modular manner, and each supplier, or component manufacturer can contribute its data to add to the network. The network can be easily drawn by hand for quick discussions and modification. The STN method is compatible to print media.

There is no loss of data when the STN graph is printed in colour. Black and white prints show the geographically dispersed lifecycle network.

The STN method is not a replacement for existing supply chain and logistics tools that handle large amounts of logistics related information including part numbers, real time tracking etc. This method is useful for the intended users as explained earlier for decision making purposes related to the product supply chain and lifecycle. The STN method have been presented to industry representatives, who acknowledged the potential usefulness of the method. User surveys of end users are planned to be carried out to estimate the level of understanding and ease of use of STN method compared to other graphical representations.

5 Conclusions

According to Winston [18], finding appropriate representation is a major part of a problem solving effort. A good representation 'makes important things explicit' and exposes 'the natural constraints inherent in the problem' [18-19]. The STN method proposes an information visualisation approach to graphical problem solving in the product lifecycle related domain. Supply chain infographics convey data in pictorial manner, but the ability to create good infographics depends on the skill of the designer. The STN graph is a generic and replicable design, from which the relationships between processes, locations, and network dependencies can be interpreted and extrapolated. An implementation of the STN method is currently being tested for its efficacy.

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