# Automated Ergonomics Assessment of Material Handling Activities

By

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#### Abstract

Manufacturing companies for decades have relied on forklifts as their workhorses for material handling. However, in recent years, productivity, cost and safety concerns have led manufacturing companies to reduce and eliminate the use of forklifts. While there are many alternatives to the traditional forklifts, tugger tow trains deliveries (tuggers) have been the common and the most effective choice for regular material handling activities within manufacturing facilities. Tugger carts are towing vehicles that can be in the form of manned or unmanned systems. The latter is generally classified as automated guided carts and are unsurprisingly more expensive than their counterparts and are still long way from becoming a convincing choice for manufacturing companies. The low profile of these tuggers enable them to tow large loads and have the ability to drop/pickup full and empty carts to/from the respective stations during a single circuit which provides great flexibility in designing the tugger routes. However, these tuggers pose new physical fatigue issues to the material handlers - tugger drivers who previously rarely left their fork trucks. On average a tugger driver will have to walk, lift, pushup and push heavy loads to and from stations between 10 to 60 feet per container. As a result, companies are forced to take into consideration these ergonomic factors when designing tugger routes and their work shift times. This study analyzes these constraints and proposes an automated process in calculating the metabolic energy expenditure of tugger drivers in manufacturing plants using metabolic energy expenditure prediction analysis. The proposed program was run for a simulated sample data created based on literature. The results provide insights about the manual material handlers' energy expenditure and its variations while performing tasks and while resting, throughout their work shifts. This information can be useful for managers to better balance the material handling jobs among multiple operators and to allow

relaxation times for proper recovery which will reduce the possibility of physical fatigue related injuries.

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#### Introduction

Lean manufacturing, safety and cost reduction concepts have become more pertinent in today's manufacturing environment than ever before. Manufacturers are forced to think faster, smarter and leaner to remain productive in their competitive market. The extent of the continuous improvement and waste reduction methodologies go beyond the manufacturing shop floor and are integrated into the entire supply chain system. Lean manufacturing practices/tools like SMED, 5S, value stream mapping, kanban, poka-yoke and much more have been widely applied in all kinds of manufacturing production facilities. Further, researchers have defended that lean is not just a tool but a way of thinking and have demonstrated its application in healthcare, business, finance, information technology and service-industries [1] where waste reduction is that of customers' time and lean thinking goes in understanding exactly what customers want and providing it when and where they want.

Material handling and logistics is one of the key components of any manufacturing environment and its supply chain. In traditional material handing methods, most manufacturers after receiving the raw materials at the dock directly moved and stored them in boxes, pallets or crates right beside the production line. To achieve this type of material handling where large crates are to be moved within the manufacturing facility, companies used Lift Trucks also known as Forklifts.

#### Forklifts

For over a century now, forklifts have been the ideal material handling solution for most manufacturing environments which replaced the old system that used pulley, ropes and cables to move heavy materials. Forklifts are safer and drivable machines that can lift, carry and move loads up to 35,000 pounds depending on their size. They are easier to operate and can be maneuvered to turn in different directions to assist material handling. While most forklifts are electrically powered, there are internal combustion engine powered ones too which are often noisy and polluting and are mostly used in applications outside the manufacturing facility. One big advantage of using a fork truck is that they can move and stack materials vertically which can save considerable inventory space.

However, forklifts are not always effective or efficient as they mostly handle only one crate/cart/box at a time. This requires excess materials to be stored alongside the production floor and substantiates the need for forklifts and operator coordination for stock replenishments. While forklifts do have the ability to maneuver in different directions, they often have limited visibility in the sides and back which poses a huge safety issue. Over the years, there have been studies researching on the ergonomics of operators in forklifts and improvements have continuously been made to make them safer[2–7]. Nonetheless, forklifts based accidents are still a high concern [8, 9] and the resulting production time loss and compensation cost has led companies to look for alternatives.

#### Lean Material Handling

With the increasing adoption of lean manufacturing concepts in production facilities over the past decade, companies have repeatedly tried to find ways to eliminate wastes in their environment to stay competitive. Lean Material Handling (LMH) was one of the main waste reduction concepts that was introduced under Toyota Production System (TPS) also known as Lean Manufacturing System (LMS) [10, 11]. The basic principle of TPS is to continuously find ways to improve the manufacturing efficiency by minimizing waste. Waste in manufacturing is applicable to both the physical waste of storing excess raw materials and finished goods as well as to the actual production process itself and lack of its standardization.

In a lean material handling system, the production lines follow a predefined assembly sequence designed during the production planning and the materials are directly driven and delivered to the operator at the assembly line when it is needed and with the exact quantity that is needed. Hence, knowing the exact information on which part is being processed at a given station at any given time, manufactures can simply deliver only those required parts to the shop floor just before it is being used. This methodology is also called Just in Time (JIT) and to be implemented properly, it requires a well-structured production planning system.

When companies that used forklifts in the past started transitioning to a lean manufacturing, they became more aware of safety concerns and tried to reduce the usage of forklifts inside the production facilities. Some companies allocated dedicated areas and routes inside their plants for forklifts and prevented them from entering areas where there were workers. Moreover, with the increased frequency of the material delivery to the production line under lean material handling practices, companies were limited by the inability of the forklifts to pick up and drop multiple materials to multiple stations in a single route. However, having more forklifts to operate more frequently to tackle this increased material handling frequency did not seem to be a productive solution. This combination of safety, productivity and lean manufacturing concerns have forced manufacturers to reduce and eliminate the use of forklifts. In order to achieve a forklift free manufacturing environment, these companies started looking for effective alternatives that can overcome these concerns and can fit in a lean material handling environment.

#### **Tugger Tow Train - Tuggers**

Tuggers are the most popular JIT solutions for replacing forklifts in manufacturing firms. They can be operated with a single operator and can tow 3-4 carts at a time depending upon their capacity. The low profile of tuggers helps keep the products close to the ground and enable them to tow large loads with less power. The tugger carts come in many designs and styles that are suitable for various material handling purposes including movement of fully loaded crates or pallets which was the original use of forklifts. But the true ability of achieving a lean material handling through tuggers is with the custom designability of the carts to fit the exact needs of any manufacturing environment.

Often, a combination of multiple specially designed carts is attached to the tugger, thereby creating a train-like setup that can be pulled around the manufacturing facility for material handling. In some applications of the tugger system, the operators deliver and pick up a fully loaded cart by just attaching and detaching it from the assembly.

The biggest disadvantage of tuggers is the need for the operator to step out/in, lift/drop and carry materials to and from the tugger during each route and at each station. On an average, a tugger operator walks between 10 to 60 feet per delivery. Most of these operators are transitioning from forklifts where they rarely left their forklift trucks during material handling activities. The increased movement by the material handling operators can limit their ability to work efficiently throughout their entire work shift and causes physical fatigue. For companies that are transitioning to tuggers as a lean manufacturing initiative, this can pose a huge resource waste, especially if there are injuries. As a result, companies are now faced with defining tugger routes whereby ergonomic load factors are an equally important constraint to that of the time required to complete a tugger route and the volumetric capacity of carts on each tugger. In this study, an automated ergonomic assessment tool is proposed that will evaluate the tugger operator's fatigue when performing the material handling tasks. The ergonomic assessment will involve a combination of Energy Expenditure Analysis (Garg), Lift and Carry Limits (NIOSH) and Push Pull Table (Snook) methodologies. For automating this assessment, the proposed solution will leverage the material handling optimization software Flow Planner.

#### **Proplanner Flow Planner**

Flow Planner is one of the products under Proplanner, a leading process engineering and management software suite whose solutions are focused on manufacturing optimization using contemporary industrial engineering techniques. Some of the innovative products under Proplanner suite include Advanced Planning & Scheduling (APS), Manufacturing Execution System (MES), Assembly Planner (AP) which includes Process Authoring, Line Balancing, Time Studies, Ergonomic Studies, FMEA, Control Plan and much more, and finally Material & Logistics Planning which includes PFEP (Part for Every Part), eKanban, eKnitting and Flow Planner which is what will be used in this study.

Flow Planner is the product that works on manufacturing material handling and uses advanced techniques to evaluate, reduce and eliminate excess material flow within manufacturing facilities. Flow Planner works as an add-on to AutoCAD and uses the factory layout drawings that are readily available at the hands of field engineers. The biggest advantage of using CAD based layout planner as compared to a simulation is that the resulting layout and its dimensions can be extracted automatically through AutoCAD while a considerable effort is required to translate simulations into actual layouts. An example of a manufacturing facility's AutoCAD plant layout is shown next page in Figure 1. In addition to the AutoCAD drawings, Flow Planner requires the part consumption and part request history data in the form of an excel spreadsheet saved as .CSV Format. This spreadsheet will have the FROM, STAGE and TO locations along with the part number and container information. An example of the route file is showed in Figure 2. There are three types of tugger routes when calculating through the Flow Planner - Tugger Analysis module. For the same operator, the tugger route can be from the storage to the staging area, staging to the production line and storage to staging to line which is used in routes where the driver also fills the tugger carts. The analysis is performed for one day at a time and different historical or random days can be evaluated. Flow Planner's algorithm takes into account the inability of tuggers to turn around an aisle path and the shortest path based transport sequence is calculated using the travelling salesman algorithm.

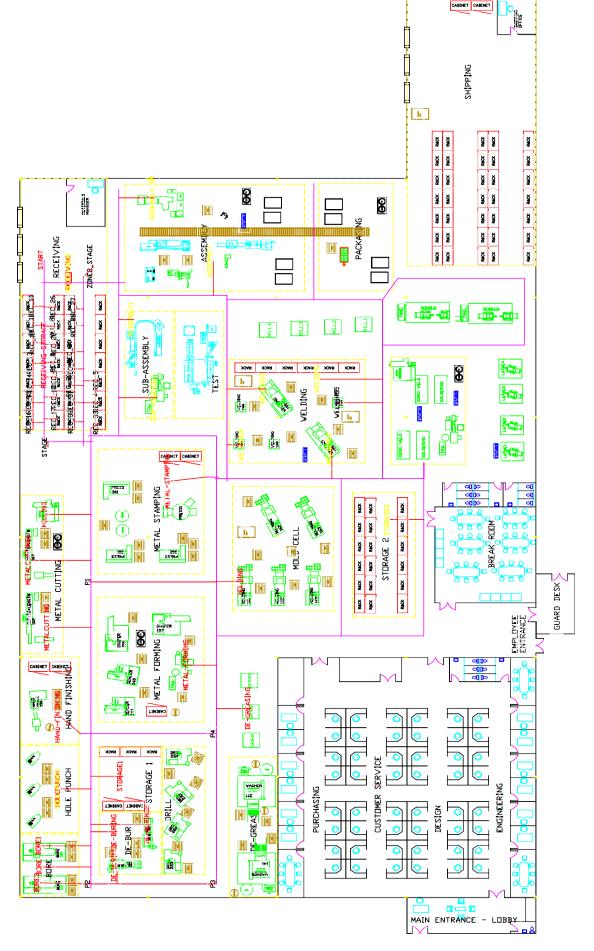
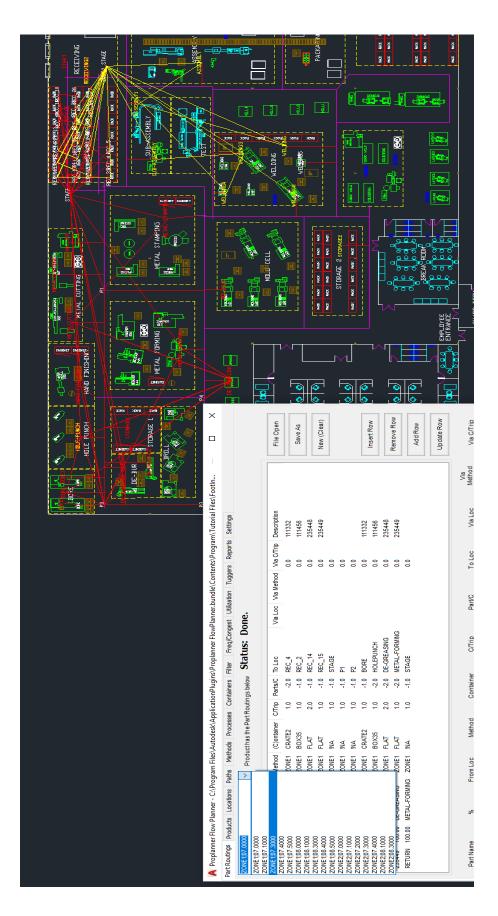


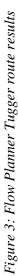
Figure1: AutoCAD factory layout

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1	*ID	Part	Container	ContQty	From	Stage	То	ETD	Direction	Load	Unload
2	1	111456	TUB	3	A	STORAGE	5	7.5	1		
3	2	111847	CART	2	D	STORAGE	6	UFM(7/10/2/.5	) 1		
4	3	111332	TUB	3	F	STORAGE	10	7.1	-1		
5	4	111445	TUB	4	L	STORAGE	9	UFM(7/10/1/1)	) -1		

Figure 2: An example of the route file which is saved in a .CSV format

After the route file is loaded, the user can select the type of flow, Straight Flow or Aisle Flow, for generating the tugger routes. Straight Flow will show the tugger routes mapped based on the shortest path possible which may not be the practical case. Aisle Flow will populate the tugger routes with the additional constraint of following the actual aisle path provided in the CAD drawing. Figure 3 shows an example result of tugger routes generated choosing a straight flow constraint. In this example there are two tugger zones Zone1 and Zone2 which represents to tuggers operated simultaneously during a day. The time period in this example is from 7 AM to 9 AM with tugger routes populated for every 10-minute interval with an assumption that even if a tugger route is shorter than 10 minutes the next route will not start immediately but only after the end of the whole 10-minute route interval. The figure also shows the Flow Planner's window where the user can select each individual route to see the sequence of the deliveries. The AutoCAD screen in the figure shows the tugger routes for each of the two zones. In this specific example the paths in red are that of Zone1 and the ones in yellow are that of Zone2. In addition to the route mappings, Flow planner also provides a summary window with all the route statistics as shown in Figure 4. Additional screen prints of the tugger study in Flow Planner is provided in the appendix section of this paper.





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Current History																			
Aggregate	Dist (Ft)	Time (Hrs)	Cost	Travel%	TugVol %	Qty	AvgTripTime (Mins)	Min Trip	Max Tr	SDEV	Avg Tra	Min Tra	Max Trav	SDEV Tra	Avg Han	Min Han	Max H	SDEV H	Container Qty
ZONE1¦07.0000	546.09	0.07	\$1.46	41.49%	64.67%	12	0.37	0.07	0.60	0.16	0.15	0.02	0.42	0.13	0.21	0.00	0.50	0.19	10
ZONE1¦07.1000	439.59	0.04	\$0.71	69.27%	0.53%	6	0.35	0.11	0.54	0.17	0.24	0.08	0.54	0.19	0.11	0.00	0.40	0.17	2
ZONE1¦07.3000	441.78	0.04	\$0.74	66.26%	9.00%	6	0.37	0.11	0.61	0.20	0.25	0.04	0.59	0.21	0.13	0.00	0.50	0.21	2
ZONE1¦07.4000	453.57	0.05	\$1.00	50.20%	42.67%	8	0.38	0.04	0.86	0.29	0.19	0.03	0.42	0.15	0.19	0.00	0.50	0.22	4
ZONE1¦07.5000	484.83	0.04	\$0.79	68.30%	21.33%	6	0.39	0.20	0.74	0.20	0.27	0.20	0.42	0.10	0.13	0.00	0.50	0.21	2
ZONE1¦08.0000	491.75	0.05	\$1.06	51.40%	10.07%	8	0.40	0.15	0.59	0.17	0.20	0.04	0.54	0.18	0.19	0.00	0.55	0.23	6
ZONE1¦08.1000	393.24	0.03	\$0.65	66.85%	0.67%	6	0.33	0.04	0.54	0.19	0.22	0.04	0.48	0.19	0.11	0.00	0.40	0.17	2
ZONE1¦08.3000	392.55	0.03	\$0.69	63.57%	21.33%	6	0.34	0.04	0.74	0.24	0.22	0.04	0.42	0.16	0.13	0.00	0.50	0.21	2
ZONE1¦08.4000	630.13	0.09	\$1.70	41.18%	21.33%	12	0.43	0.05	0.76	0.21	0.18	0.03	0.42	0.13	0.25	0.00	0.50	0.21	8
ZONE1¦08.5000	444.59	0.04	\$0.83	59.71%	42.67%	6	0.41	0.09	1.08	0.35	0.25	0.09	0.42	0.14	0.17	0.00	0.75	0.30	4
ZONE2¦07.0000	237.18	0.02	\$0.43	61.26%	9.00%	4	0.32	0.06	0.58	0.21	0.20	0.06	0.33	0.16	0.13	0.00	0.25	0.14	2
ZONE2¦07.1000	282.38	0.04	\$0.73	42.96%	20.94%	7	0.31	0.08	0.57	0.14	0.13	0.02	0.32	0.12	0.18	0.00	0.25	0.12	6
ZONE2¦07.2000	220.75	0.02	\$0.41	59.54%	24.89%	4	0.31	0.17	0.45	0.15	0.18	0.17	0.20	0.02	0.13	0.00	0.25	0.14	2
ZONE2¦07.3000	304.48	0.04	\$0.84	40.36%	42.67%	8	0.31	0.09	0.46	0.12	0.13	0.03	0.21	0.06	0.19	0.00	0.25	0.12	6
ZONE2¦07.4000	400.22	0.03	\$0.69	64.01%	2.40%	5	0.42	0.22	0.65	0.16	0.27	0.09	0.40	0.13	0.15	0.00	0.25	0.14	6
ZONE2¦08.1000	324.96	0.03	\$0.69	52.00%	30.33%	6	0.35	0.09	0.58	0.19	0.18	0.04	0.33	0.11	0.17	0.00	0.25	0.13	4
ZONE2¦08.3000	284.93	0.03	\$0.65	48.71%	24.89%	6	0.32	0.10	0.53	0.16	0.16	0.07	0.28	0.08	0.17	0.00	0.25	0.13	4
Total	6,773.01	0.70	\$14.08	53.44%	22.90%	116													
Right-Click to Co	py Screen								F	Return	۲	) Aggregates		O Routes					

Figure 4: Flow Planner Tugger route statistics

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Prom     To     Free     Calc Dist/Trip (Ft)     Eff. Dist/Trip (Ft)     User Dist/Trip (Ft)     Total I_Var     Method Type       ONE_107.0000     STAGE     REC_4     1.000     0.5     0.5     None     0.00     0.01     0     TUG       ONE_107.0000     REC_4     REC_2     1.000     0.2     0.2     None     0.00     0.00     0     TUG       ONE_107.0000     REC_14     REC_15     1.000     0.2     0.2     None     0.00     0.00     0     TUG       ONE_107.0000     REC_15     1.000     0.3     0.3     None     0.00     0.00     0     TUG       ONE_107.0000     STAGE     P1     1.000     0.3     0.3     None     0.00     0.00     0     TUG       ONE_107.0000     P2     BORE     1.000     0.8     0.8     None     0.00     0.00     0     TUG       ONE_107.0000     DE-GREASING     METAL-FORNING     1.000     0.5     0.5     None     0.00     0.	oduct			Aggregat	e paths shown l	below		Status	Selecting	Paths: Done				
ONE:107.0000   STAGE   REC_4   1.000   0.5   0.5   None   0.00   0.00   0   TUG     ONE:107.0000   REC_2   REC_14   REC_15   1.000   0.2   0.2   None   0.00   0.00   0   TUG     ONE:107.0000   REC_14   REC_15   1.000   0.2   0.2   None   0.00   0.00   0   TUG     ONE:107.0000   REC_14   REC_15   1.000   0.3   0.3   None   0.00   0.00   0   TUG     ONE:107.0000   STAGE   P1   1.000   0.9   0.9   None   0.00   0.00   0   TUG     ONE:107.0000   P2   BORE   1.000   1.5   1.5   None   0.00   0.00   0   TUG     ONE:107.0000   P2   BORE   1.000   1.3   1.3   None   0.00   0.01   0   TUG     ONE:107.0000   PEGREASING   DOE   1.3   1.3   None   0.00   0.00   0   TUG     ONE:107.10000   STAGE   P1   <	ggregate Pa	ith Inform	ation								1	1	1	
ONE_107.0000   REC_4   REC_2   1.000   0.9   0.9   None   0.000   0.000   0   TUG     ONE_107.0000   REC_14   1.000   0.2   0.2   None   0.000   0.000   0   TUG     ONE_107.0000   REC_15   STAGE   1.000   0.3   0.3   None   0.000   0.000   0   TUG     ONE_107.0000   REC_15   STAGE   1.000   0.3   0.3   None   0.000   0.000   0   TUG     ONE_107.0000   P1   P2   1.000   1.5   1.5   None   0.000   0.000   0   TUG     ONE107.0000   P2   BORE   1.000   0.8   0.8   None   0.000   0.000   0   TUG     ONE107.0000   BORE   HOLEPUNCH   DE-GREASING   1.000   1.3   1.3   None   0.000   0.000   0   TUG     ONE107.0000   DE-GREASING   1.000   2.1   2.1   None   0.000   0.000   0   TUG     ONE107.10000   REC_3   1.000	Aggregate N	lame Fi	rom		То	Fre	q Calc Dist/Trip (Ft)	Eff. Dist/Trip (Ft)	User Dist/Trip (Ft)	Total Travel Time (Hrs)	Total L/UL Time (Hrs)	Total \$	Method Typ	pe
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ONE:107.0000   REC_14   REC_15   1.000   0.2   0.2   None   0.00   0.00   0   TUG     ONE:107.0000   REC_15   STAGE   1.000   0.3   0.3   None   0.00   0.00   0   TUG     ONE:107.0000   P1   P2   1.000   1.5   1.5   None   0.00   0.00   0   TUG     ONE:107.0000   P2   BORE   1.000   0.3   0.3   None   0.00   0.00   0   TUG     ONE:107.0000   P2   BORE   1.000   0.8   0.8   None   0.00   0.01   0   TUG     ONE:107.0000   BORE   HOLEPUNCH   DEGREASING   1.000   1.3   1.3   None   0.00   0.01   0   TUG     ONE:107.0000   METAL-FORMING   STAGE   1.000   0.5   0.5   None   0.00   0.00   0   TUG     ONE:107.1000   REC_3   1.000   0.6   0.6   None   0.00   0.00   0   TUG     ONE:107.1000   REC_3   1.000 <td>ONE1¦07.0</td> <td>000 R</td> <td>EC_4</td> <td></td> <td>REC_2</td> <td>1.00</td> <td>0.9</td> <td>0.9</td> <td>None</td> <td>0.00</td> <td>0.00</td> <td>0</td> <td>TUG</td> <td></td>	ONE1¦07.0	000 R	EC_4		REC_2	1.00	0.9	0.9	None	0.00	0.00	0	TUG	
ONE:107.0000   REC_15   STAGE   1.000   0.3   0.3   None   0.00   0.00   0   TUG     ONE:107.0000   STAGE   P1   1.000   0.9   0.9   None   0.00   0.00   0   TUG     ONE:107.0000   P2   BORE   1.000   0.3   0.3   None   0.00   0.00   0   TUG     ONE:107.0000   P2   BORE   HOLEPUNCH   1.000   0.8   0.8   None   0.00   0.01   0   TUG     ONE:107.0000   BORE   HOLEPUNCH   1.000   0.8   0.8   None   0.00   0.01   0   TUG     ONE:107.0000   DE-GREASING   METAL-FORMING   IAGE   1.000   0.5   0.5   None   0.00   0.00   0   TUG     ONE:107.1000   STAGE   REC_3   1.000   0.6   0.6   None   0.00   0.00   0   TUG     ONE:107.1000   REC_3   STAGE   1.000   0.4   0.4   None   0.00   0.00   0   TUG     ONE:107.100	ONE1 07.0	000 R	EC_2		REC_14	1.00	0.2	0.2	None	0.00	0.00	0	TUG	
ONE II 07.0000     STACE     P1     1.000     0.9     0.9     None     0.00     0.00     0     TUG       ONE II 07.0000     P1     P2     1.000     1.5     1.5     None     0.00     0.00     0     TUG       ONE II 07.0000     P2     BORE     1.000     0.3     0.3     None     0.00     0.00     0     TUG       ONE II 07.0000     BORE     HOLEPUNCH     L000     0.3     1.3     None     0.00     0.01     0     TUG       ONE II 07.0000     HOLEPUNCH     DE-GREASING     METAL-CORNING     1.000     0.5     None     0.00     0.01     0     TUG       ONE II 07.0000     METAL-CORNING     TAGE     1.000     0.5     0.5     None     0.00     0.00     0     TUG       ONE II 07.1000     REC_3     STAGE     1.000     0.6     0.6     None     0.00     0.00     0     TUG       ONE II 07.1000     FLG     MEC_3     STAGE     1.000     0.5	ONE1¦07.0	000 R	EC_14		REC_15	1.00	0.2	0.2	None	0.00	0.00	0	TUG	
ONE107.0000   P1   P2   1.000   1.5   1.5   None   0.00   0.00   0   TUG     ONE107.0000   P2   BORE   1.000   0.3   0.3   None   0.00   0.00   0   TUG     ONE107.0000   BORE   HOLEPUNCH   1.000   0.8   0.8   None   0.00   0.00   0   TUG     ONE107.0000   BORE   HOLEPUNCH   De-GREASING   METAL-FORMIN   1.000   0.5   None   0.00   0.01   0   TUG     ONE107.0000   DE-GREASING   METAL-FORMINS   STAGE   1.000   0.5   None   0.00   0.00   0   TUG     ONE107.0000   DE-GREASING   METAL-FORMING   STAGE   1.000   0.6   0.6   None   0.00   0.00   0   TUG     ONE107.1000   STAGE   P1   1.000   0.9   None   0.00   0.00   0   TUG     ONE107.1000   STAGE   1.000   0.4   0.4   None   0.00   0.01   0   TUG     ONE107.1000   P2 </td <td>ONE1¦07.0</td> <td>000 R</td> <td>EC_15</td> <td></td> <td>STAGE</td> <td>1.00</td> <td>0.3</td> <td>0.3</td> <td>None</td> <td>0.00</td> <td>0.00</td> <td>0</td> <td>TUG</td> <td></td>	ONE1¦07.0	000 R	EC_15		STAGE	1.00	0.3	0.3	None	0.00	0.00	0	TUG	
ONE:107.0000   P2   BORE   1.000   0.3   0.3   None   0.00   0.00   0   TUG     ONE:107.0000   BORE   HOLEPUNCH   1.000   0.8   0.8   None   0.00   0.01   0   TUG     ONE:107.0000   BORE   HOLEPUNCH   DE-GREASING   METAL-FORMING   1.000   1.3   1.3   None   0.00   0.01   0   TUG     ONE:107.0000   METAL-FORMING   STAGE   1.000   0.5   0.5   None   0.00   0.00   0   TUG     ONE:107.0000   METAL-FORMING   STAGE   1.000   0.6   0.6   None   0.00   0.00   0   TUG     ONE:107.1000   REC_3   STAGE   1.000   0.6   0.6   None   0.00   0.00   0   TUG     ONE:107.1000   P42   DE   1.000   1.5   1.5   None   0.00   0.00   0   TUG     ONE:107.1000   P2   DE	ONE1 07.0	000 S	TAGE		P1	1.00	0.9	0.9	None	0.00	0.00	0	TUG	
ONE 1107.0000     P2     BORE     1.000     0.3     0.3     None     0.00     0.00     0     TUG       ONE 1107.0000     BOCRE     HOLEPUNCH     1.000     0.8     0.8     None     0.00     0.01     0     TUG       ONE 1107.0000     DE-GREASING     METAL-FORMING     1.000     0.5     0.5     None     0.00     0.00     0     TUG       ONE 1107.0000     METAL-FORMING     STAGE     1.000     0.5     0.5     None     0.00     0.00     0     TUG       ONE 1107.0000     METAL-FORMING     STAGE     1.000     0.6     0.6     None     0.00     0.00     0     TUG       ONE 1107.1000     STAGE     P1     1.000     0.6     0.6     None     0.00     0.00     0     TUG       ONE 1107.1000     P4     P1     1.000     0.5     1.5     None     0.00     0.00     0     TUG       ONE 1107.1000     P2     DEBURING     STAGE     1.000     0.6	ONE1:07.0	000 P	1		P2	1.00	1.5	1.5	None	0.00	0.00	0	TUG	
ONE 1107.0000     BORE     HOLEPUNCH     1.000     0.8     0.8     None     0.00     0.01     0     TUG       DNE:107.0000     HOLEPUNCH     DE-GREASING     1.000     0.5     0.5     None     0.00     0.00     0     TUG       DNE:107.0000     METAL-FORMING     STAGE     1.000     0.5     0.5     None     0.00     0.00     0     TUG       DNE:107.0000     METAL-FORMING     STAGE     1.000     0.6     0.6     None     0.00     0.00     0     TUG       DNE:107.1000     STAGE     P1     1.000     0.9     None     0.00     0.00     0     TUG       DNE:107.1000     P4     P2     1.000     1.5     1.5     None     0.00     0.00     0     TUG       DNE:107.1000     P2     DE-BURING     1.000     0.4     0.4     None     0.00     0.00     0     TUG       DNE:107.1000     P4     DE-BURING     1.000     0.6     0.6     None			2		BORE			0.3	None	0.00	0.00	0	TUG	
ONE 107.0000     HOLEPUNCH     DE-GREASING     1.000     1.3     1.3     None     0.00     0.01     0     TUG       ONE 107.0000     DE-GREASING     METAL-FORMING     STAGE     1.000     0.5     0.5     None     0.00     0.01     0     TUG       ONE 107.0000     DE-GREASING     METAL-FORMING     STAGE     1.000     0.6     0.6     None     0.00     0.00     0     TUG       ONE 107.1000     STAGE     1.000     0.6     0.6     None     0.00     0.00     0     TUG       ONE 107.1000     STAGE     P1     1.000     0.9     0.9     None     0.00     0.00     0     TUG       ONE 107.1000     P1     P2     1.000     1.5     1.5     None     0.00     0.00     0     TUG       ONE 107.1000     P2     DE-BURING     1.000     0.4     0.4     None     0.00     0.01     0     TUG       ONE 107.1000     DE-BURING     1.000     0.6     0.6 <td></td>														
ONE 107.0000   DE-GREASING   METAL-FORMING   1.000   0.5   0.5   None   0.00   0.01   0   TUG     ONE 107.0000   METAL-FORMING   STAGE   1.000   0.6   0.6   None   0.00   0.00   0   TUG     ONE 107.0000   METAL-FORMING   STAGE   1.000   0.6   0.6   None   0.00   0.00   0   TUG     ONE 107.1000   REC_3   STAGE   1.000   0.6   0.6   None   0.00   0.00   0   TUG     ONE 107.1000   STAGE   P1   1.000   0.9   0.9   None   0.00   0.00   0   TUG     ONE 107.1000   P1   P2   1.000   1.5   1.5   None   0.00   0.00   0   TUG     ONE 107.1000   P2   DE0URING   STAGE   1.000   0.4   0.4   None   0.00   0.00   0   TUG     ONE 107.3000   STAGE   1.000   0.6   0.6   None   0.00   0.00   0   TUG     ONE 107.3000   REC_5				сн										
ONE 1107.0000     METAL-FORMING     STAGE     1.000     2.1     2.1     None     0.00     0.00     0     TUG       ONE 1107.1000     STAGE     REC_3     1.000     0.6     0.6     None     0.00     0.00     0     TUG       ONE 1107.1000     STAGE     P1     1.000     0.6     0.6     None     0.00     0.00     0     TUG       ONE 1107.1000     STAGE     P1     1.000     0.9     0.9     None     0.00     0.00     0     TUG       ONE 1107.1000     P1     P2     1.000     1.5     1.5     None     0.00     0.01     0     TUG       ONE 1107.1000     P2     DEBURING     STAGE     1.000     2.3     2.3     None     0.00     0.01     0     TUG       ONE 1107.3000     REC_5     STAGE     1.000     0.6     0.6     None     0.00     0.01     0     TUG       ONE 1107.3000     REC_5     STAGE     1.000     0.6     0.6														
DNE1107.1000     STAGE     REC_3     1.000     0.6     0.6     None     0.00     0.00     0     TUG       DNE1107.1000     REC_3     STAGE     1.000     0.6     0.6     None     0.00     0.00     0     TUG       DNE1107.1000     STAGE     P1     1.000     0.9     0.9     None     0.00     0.00     0     TUG       DNE1107.1000     P1     P2     1.000     1.5     1.5     None     0.00     0.00     0     TUG       DNE1107.1000     P2     DE-BURING     1.000     0.4     0.4     None     0.00     0.00     0     TUG       DNE1107.1000     DE-BURING     STAGE     1.000     2.3     2.3     None     0.00     0.01     0     TUG       DNE1107.3000     REC_5     STAGE     1.000     0.6     0.6     None     0.00     0.00     0     TUG       Save As     Erase Selected Path     Erase ALL Listed Paths     Erase ALL DWG Path     EditRedo Selected														
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ONE 1107.1000     DE-BURING     STAGE     1.000     2.3     2.3     None     0.00     0.00     0     TUG       ONE 1107.2000     STAGE     REC_5     1.000     0.6     0.6     None     0.00     0.01     0     TUG       ONE 1107.2000     STAGE     REC_5     STAGE     1.000     0.6     0.6     None     0.00     0.01     0     TUG       Save As     Erase Selected Path     Erase ALL Listed Paths     Erase ALL DWG Paths     Edit/Redo Selected     User Distance (M)     None     Update     Update     Update     Update     Update     Update     Update     Update     Query Path     Erase Path     Erase Path     Erase Path     Erase Path     Erase Path     Delete     On Line     On Line     On Line     Erase Path     Save Paths (Fill     Save Paths (Fill     Save Paths (Fill)     Sa														
ONE 1107.3000   STAGE   REC_5   1.000   0.6   0.6   None   0.00   0.01   0   TUG     ONE 1107.3000   REC_5   STAGE   1.000   0.6   0.6   None   0.00   0.00   0   TUG     Save As   Erase Selected Path   Erase ALL Listed Paths   Erase ALL DWG Paths   Edit/Redo Selected   User Distance (M)   None   0.00   0   TUG     Save As   Erase Selected Path   Erase ALL DWG Paths   Edit/Redo Selected   User Distance (M)   None   0.00   0   TUG     Save As   Erase Selected Path   Erase ALL DWG Paths   Edit/Redo Selected   User Distance (M)   None   0.00   0   TUG     Save As   Erase ALL DWG Paths   Erase ALL DWG Paths   Edit/Redo Selected   User Distance (M)   None   0 <t< td=""><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></t<>														
ONE 1:07.3000   REC_5   STAGE   1.000   0.6   0.6   None   0.00   0.00   0   TUG     Save As   Erase Selected Path   Erase ALL Listed Paths   Erase ALL DWG Paths   Edit/Redo Selected   User Distance (M)   None   0.00   0   TUG     Save As   Erase Selected Path   Erase ALL Listed Paths   Erase ALL DWG Paths   Edit/Redo Selected   User Distance (M)   None   Update   Update   Update   Update   Congest Arrows   Update   Path Arrows   Delete   On Line   Delete   Congest Arrows   Delete   On Line   Edit/Redo Path				١G										
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*Figure 5: Generated routes' path information in Flow Planner* 

## Methodology

Understanding the justification for the migration to tuggers from forklifts and observing the resulting increase in manual material handling activities performed by the operators, it is now clear why a systematic method to analyze the ergonomics of these activities is necessary. Also, having such an ergonomic analysis of manual material handling activities can be useful for manufacturers to determine whether to incorporate additional longer or frequent rest breaks or any other necessary allowances.

In this research, energy expenditure will be used as the physiological measurement to measure the physical fatigue which can impact the work performance and productivity of the tugger operators [12]. There are various research works in the past that have formulated methods and models for the ergonomic energy analysis of physical activities. According to the prediction model by [13], a combination of simple tasks or activity elements together form a job and the overall energy expenditure of the job can be predicted by knowing the individual activity energy expenditures and the time duration of those tasks. Mathematically:

$$\overline{E_{Job}} = \frac{\sum_{i=1}^{n_p} E_{posture} \cdot t_i + \sum_{i=1}^{n} \Delta E_{task_i}}{T}$$

Where,

- $\begin{array}{ll} \overline{E_{job}} & = \text{Average energy expenditure rate of the job (Kcal/min)} \\ \\ E_{posture} & = \text{Metabolic energy expenditure rate due to maintenance of } i^{th} \text{ of the job} \\ \\ \\ (\text{Kcal/min}) \\ \\ \\ t_i & = \text{Time duration for the } i^{th} \text{ posture (min)} \end{array}$
- $n_p$  = Total number of body postures employed in the job

$\Delta E_{task_i}$	= Net metabolic energy expenditure of the $i^{th}$ task in steady state (Kcal)
n	= Total number of tasks in the given job
Т	= Time duration of the job (min)

In this paper, the job of the tugger operator can be similarly split down into simple activities. To define these tasks let's take a simple example tugger route using the same factory layout shown in Figure 1. Let's assume there is tugger route where a tugger operator starts and ends at ZONE2\_STAGE located at the top right corner of the layout and the job consists of two of the following tasks.

- 1. Load part P1 from rack REC\_27 on to the tugger
- 2. Unload part P1 from the tugger at the station WELDING3

These two tasks encapsulate the majority of the tugger operator's material handling duties and the entire tugger study of Flow Planner can be boiled down to a series of Load & Unload activities. The individual metabolic activities that will be considered for these two tasks and later for automating the calculations in this study is listed below.

- 1. Load part P1 from rack REC\_27 on to the tugger
  - 1.1 **Drive** tugger from ZONE2\_STAGE to REC\_27
  - 1.2 Climb down the tugger
  - 1.3 Walk to the rack REC\_27
  - 1.4 Lift part P1 from the rack
  - 1.5 Carry part P1 to the back of tugger
  - 1.6 Lower part on tugger
  - 1.7 Walk to front of the tugger

1.8 Climb up the tugger

- 2. Unload part P1 from the tugger at the station WELDING3
  - 2.1 **Drive** tugger to WELDING3
  - 2.2 Climb down the tugger
  - 2.3 Walk to the back of the tugger
  - 2.4 Lift part P1 of the tugger

2.5 Carry part P1 to the shelf at WELDING3 station

- 2.6 Lower part on the shelf
- 2.7 Walk back to the tugger
- 2.8 Climb up the tugger

It can be inferred that the Loading and Unloading tasks constitute of the same set of eight

activities - Drive, Walk, Carry, Lift, Lower and Climb. The metabolic energy expenditure

formulas for these activities were obtained from the literature [13] and are listed below.

Driving - Body posture maintenance,

$$E_{sitting} = 0.023 \text{ x BW}$$

Walking,

$$E_{\text{walk}} = 10^{-2} [51 + 2.54 \text{ BW x V}^2 + 0.379 \text{ BW x G x V}]$$

Carrying loads held against thighs or waist,

$$E_{carry} = 10^{-2} [68 + 2.54 \text{ BW x V}^2 + 4.63 \text{L x V}^2 + 4.62 \text{L} + 0.379 (\text{L} + \text{BW})\text{G x V}]$$

Stoop Lift,

$$E_{\text{lift}} = 10^{-2} [0.325 \text{ BW} (0.81 - h_1) + (1.41 \text{L} + 0.76 \text{ S x L})(h_2 - h_1)]$$

Stoop Lower,

$$E_{\text{lower}} = 10^{-2} [0.268 \text{ BW} (0.81 - h_1) + 0.675(h_2 - h_1) + 5.22 \text{ S} (0.81 - h_1)]$$

Climb up,

 $E_{up} = 10^{-2} [28.9 + 0.0635 \text{ BW}](h_2 - h_1)/9$ 

Climb down,

$$E_{down} = 10^{-2} [11.4 + 0.025 \text{ BW}](h_1 - h_2)/9$$

Where,

E = Metabolic Rate (Kcal/min),

V = Speed of walking (m/s),

BW = Body Weight (Kg),

L = Mass of the load (Kg)

S = Gender; 1 for Males; 0 for Females

 $h_1$  = Vertical height from the floor, starting point for lift and end for lower (m)

 $h_2$  = Vertical height from the floor, end for lift and start for lower (m)

G = Grade of the factory floor (%)

It should be noted that the units for the metabolic energy expenditure is Kcal which is equivalent to one food gram calorie(cal). One food calorie is the amount of energy needed to raise the temperature of 1 gram of water 1 degree Celsius. Hence, the calories that can be found in the back of food items can be directly compared to their Kcal equivalents. For example, if a can of soda says it has 200 cal in it, what it really means is it has 200,000 regular calories which is equivalent to 200 Kcal. The same can be applied to metabolic exercise energy calories, when the exercise charts mention that for every mile a person runs, he or she burns about 100 cal, it refers to 100 Kcal. For the duration of this study, whenever the word Kcal is mentioned, it can be directly interpreted as the food calories (1Kcal = 1 cal).

#### **Automated Energy Expenditure Calculation**

To automate the energy expenditure calculations, the loading and unloading tugger operator's tasks were split into the eight individual activities as mentioned above. With the available information about the walking distance, walking time, etc. and with the following assumptions for the rest, an excel VBA program was written as part of the tugger-ergonomics study.

#### Assumptions:

- 1. The tugger operator is male and S = 1
- 2. Operator's body weight = 170 lbs.
- 3. The factory floor is flat and the grade, G = 0
- 4. The start and end heights,  $h_1$ ,  $h_2$  when lifting a part from the tugger is always 10 and 35 inches respectively. The values can be reversed when lowering a part on the tugger.
- 5. The start and end heights,  $h_1$ ,  $h_2$  when lifting a part from the shelf is always 15 and 35 inches respectively. The values can be reversed when lowering a part on the shelf.
- 6. Driving the tugger is a seated posture maintenance activity.
- 7. Walking to the tugger back from front and to the front from the back (Activities 1.7 and 2.3 resp.) will account for 20% of the total walking distance of the Load/Unload task. And walking/carrying distance to the shelf/returning to the tugger would account for 40% of the total walking distance each.

At the basic level, the excel program file created as part of this study, will have two sheets where the first one will have the UI buttons for user interaction with the program, to clear and to regenerate the study. The user will have to save out the tugger path statistics data as a csv file which can be found under the Paths tab of Flow Planner after the tugger routes are generated (show in Figure 5). The user will have to enter the location of this csv file in Sheet1 of the program and click generate. The program will automatically import the path statistics file onto Sheet2. Although the example study shown in Figure 3 and Figure 4 were for two tugger Zone operators, in a real manufacturing setting there can be more. The program will create a sheet for each of the Zone Operator with the tasks split down to basic activities for the entire work day. For all the material handling activities, the program will auto-populate all the necessary fields based on the valued obtained from the Flow Planner output file and the assumptions made for this study. Using the respective activity energy expenditure formulas and the parameter values from Flow Planner, the program will automatically calculate the metabolic energy expenditures for these activities. Additionally, the program will also populate a graph of the cumulative energy expenditure vs time for the tugger activities for the entire work duration. The energy expenditure analysis sheet from this program for a sample data is shown in Figure 6. More detailed screen prints of this excel based program can be found in the appendix section of this paper.

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	Walking to shelf		1.00	0.0				4.53		0.07	0.13	0.22												
	Lift part from shelf Carry part to tugger-b	ack	1.00	0.0		0 35.00	25.00	4.53	0.:		0.26	0.53		80.00						_	_			
	Lower part to tugger-to		1.00	0.0		0 15.00		4.53		13 0.15	0.28	0.62		70.00						_				
	Walking to tugger-fro		1.00	0.0		43.00	2.5.00	2.26	0.0		0.40	0.80								/				
	Climb Up		1.00	0.01		0 10.00			0.1	0.34	0.41	1.14		60.00						1				
	Drive	REC 2 REC			0.0				0.0		0.44	1.15		F 0 00					_					
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	Walking to shelf		1.00	0.0	0			5.81	0.0	0.08	0.47	1.36		¥ 40.00				/						
	Lift part from shelf		1.00		10.0	0 35.00	25.00		0.:	13 0.31	0.59	1.67		Je l			~	·						
	Carry part to tugger-b	ack	1.00	0.0	0		25.00	5.81	0.0	0.12	0.62	1.79		<sup>20</sup> 30.00								- 1		
	Lower part on tugger		1.00		35.0	0 15.00	25.00			13 0.15	0.74	1.94		20.00										
	Walking to tugger-fro	ont	1.00	0.0				2.90	0.0	01 0.04	0.75	1.98		20.00										
	Climb Up		1.00		0.0	0 10.00				0.34	0.75	2.32		10.00	<i>[</i>									
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	Climb Down		1.00			0.00				0.13	0.78	2.45		0.00 🖡						,				
	Walking to shelf		1.00	0.0				5.76		0.08	0.80	2.53		0.0	0 20.00	40.00	60.0			100.00 1	20.00	140.00		
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	Carry part to tugger-b		1.00	0.0		0 15.00	25.00	5.76	0.0		0.95	2.96												
	Lower part on tugger Walking to tugger-fro		1.00	0.0		0 15.00	25.00	2.88	0.0		1.08	3.15												
	Climb Up	m	1.00	0.0		0 10.00		2.00	0.0	0.34	1.09	3.49												
	Drive	REC 15 REC			0.0	10.00			0.	16 0.03	1.05	3.52												
	Climb Down		1.00		10.0	0 0.00			0	0.13	1.25	3.65												
	Walking to tugger-ba	sck	1.00	0.0				19.44	0.0		1.33	3.93												
	Lift part from tugger		1.00			0 35.00	25.00		0.0		1.41	4.17												
	Carry part to Shelf		1.00	0.0	0		25.00	38.88	0.1	16 0.79	1.57	4.96												
	Lower part on Shelf		1.00		35.0	0 10.00	25.00		0.0	0.20	1.66	5.16												
	Walking to tugger		1.00	0.0				38.88	0.:	16 0.57	1.82	5.73												
	Climb Up		1.00		0.0	0 10.00				0.34	1.82	6.07												
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	Climb Down	-	1.00			0.00		21.02		0.13	2.37	6.30 6.61												
	Walking to tugger-ba Lift part from tugger	ICK	1.00	0.0		0 35.00		21.02	0.0	09 0.31	2.45	6.85												
	Carry part to Shelf		1.00	0.0		0 33.00		42.03	0.:		2.74	7.71												
	Lower part on Shelf		1.00	0.01		0 10.00		-4.03	0.0		2.71	7.91												
	Walking to tugger		1.00	0.0			20.00	42.03		18 0.61	2.97	8.52												
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Figure 6: Sample results from the automated energy expenditure caculaton program

#### **Results and Analysis**

The excel-based energy expenditure program was run for a sample data of two tugger operators Zone1 and Zone2 working for a duration of two hours. The sample data used for this study are shown in the Figures 3, 4 and 5. The tugger routes in Flow Planner are split into 10-minute intervals and the tugger routes trips need not necessarily occur during every interval which can be observed in Figure 4. In this sample data, within the two-hour window from 7.00 AM to 9.00AM, which has twelve 10-minute route intervals, Zone1 operator has work only during ten of those route intervals. Similarly, for the same two-hour window, Zone2 operator completes only seven routes. In all the route intervals, the operators complete the route much lesser than ten minutes. For a better understanding, the exact route completion times for the zone operators in the sample data is shown below in Table 1.

No.	<b>Route Interval</b>	Route completio	n time (min)
		Zone1	Zone 2
1	7.00 AM	5.86	2.16
2	7.10 AM	2.67	3.18
3	7.20 AM	-	1.64
4	7.30 AM	2.83	3.43
5	7.40 AM	4.01	3.01
6	7.50 AM	2.91	-
7	8.00 AM	3.90	-
8	8.10 AM	2.49	3.24
9	8.20 AM	-	-
10	8.30 AM	2.60	2.99
11	8.40 AM	6.48	-
12	8.50 AM	3.32	-

Table 1. Route completion times of the zone operators in the sample data

The program was run first without considering any possible energy recovery during the skipped routes or during the idle times within each route interval. The cumulative energy expenditures obtained for the operators for the two-hours were 75.58 Kcal and 40.83 Kcal respectively. The metabolic energy expenditure vs time graph for the two operators is shown in Figures 7 and 8 below.

It can be observed that the energy expenditure starts from zero and just keeps accumulating as the operators perform task during each of the route intervals. During the routes skipped by the operators and during the time difference between the route interval time (10 minutes) and actual route completion time, the operators are idle and no energy expenditure happens during these times.

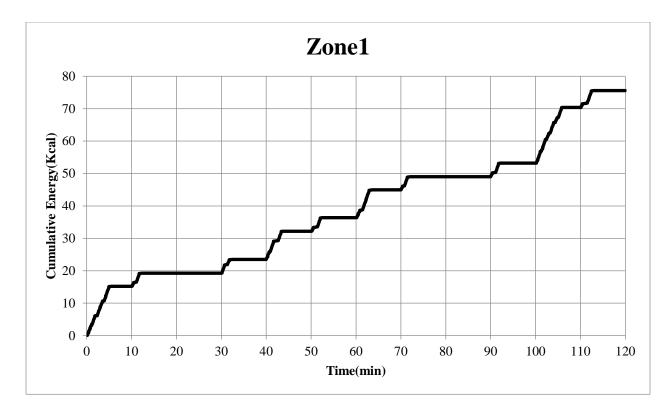


Figure 7: Cumulative Energy vs Time graph for Zone1 operator



Figure 8: Cumulative Energy vs Time graph for Zone2 operator

The energy expenditure graph as shown in the Figures 7 and 8 does not provide significant understandings for a manufacturer since the steady state cumulative metabolic energy expenditure just continues to increase with time. However, incorporating rest allowances and visualizing the energy peaks during an operator's work duration would provide great insights as

to whether the operators are working beyond their limits and are prone to physical fatigue related

injuries.

In the study [14], resting metabolic energy unit MET, has been defined as the amount of oxygen consumed at an idle resting state. The literature also has defined that an average person of 70-kg body weight spends about 1.3 Kcal every minute during rest.

Additionally, the Garg model explains that the net metabolic rate for a job is the difference between the total steady state and the resting metabolic rates.

$$\Delta E = E_{task} - E_{rest}$$

Where,

$\Delta E$	= Net metabolic energy expenditure (Kcal)
E <sub>task</sub>	= Total steady state metabolic energy expenditure (Kcal)
E <sub>rest</sub>	= The resting (standing or sitting) energy expenditure (Kcal)

These two criteria for resting energy expenditure were then incorporated to the tugger study in this paper. As observed before, the actual route completion times of the zone operators are all less than the 10-minute route interval time. So, we included a "RESTING" activity at the end of these routes for the time difference between the actual route time and for the time during the skipped routes. Since our assumption of the body weight of operator was 170 lbs. which is equivalent to 77.11Kgs, the energy expenditure rate was calculated to be 1.33 Kcal/min. Hence,

the resting energy expenditure of a tugger operator was defined as the 1.33 times the resting time in min for each route.

Resting energy expenditure formula,

 $E_{resting} = 1.33 t_{rest}$ 

Here in this sample study, the  $t_{rest}$  will be the difference of the route interval time (10 mins) and the actual time spent on tasks in that interval. Additionally. the resting energy expenditure can vary depending on many external factors like the ambience, oxygen availability, etc. and operator health factors, age, body weight, etc. Hence, we incorporated an additional UI input field for the energy threshold. This will be used as the limiting energy value and all the activities with energy expenditure values below this value will be considered as resting activities and will be subtracted from the cumulative energy expenditure value.

The same analysis was now performed again after incorporating the resting considerations. The total net metabolic energy expenditure for the Zone1 operator at the end of the two-hour work duration was calculated to be 9.13 Kcal. Once again, this value is the net value and does not mean that the operator has only spent about 9.13 Kcal during this period. The interpretation of this analysis is that over the two-hour period, the operator has spent some energy during activities and has also recovered some energy during the idle-resting durations. It should also be noted that when considering resting, the energy expenditure will not start or recover below zero but will meet at the basal resting energy expenditure value which was defined earlier as 1.33 Kcal/min for this study. Interestingly, for the Zone2 operator, since the routes durations are shorter and skipped multiple routes, there is enough time for the operator to recover the spent energy to return to the resting energy expenditure minimum of 1.33 Kcal.

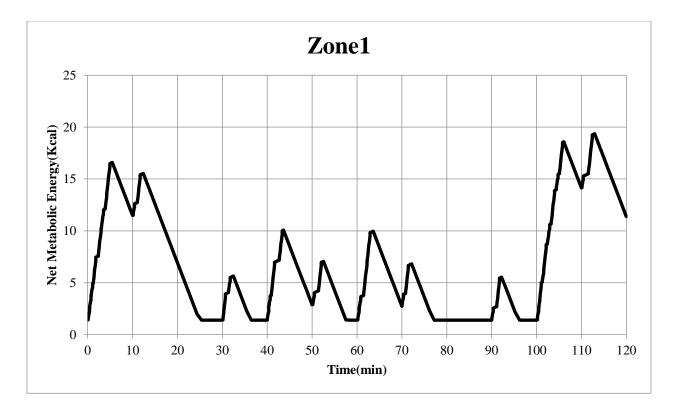


Figure 9: Net Metabolic Energy vs Time graph for Zone1 operator including resting energy recovery

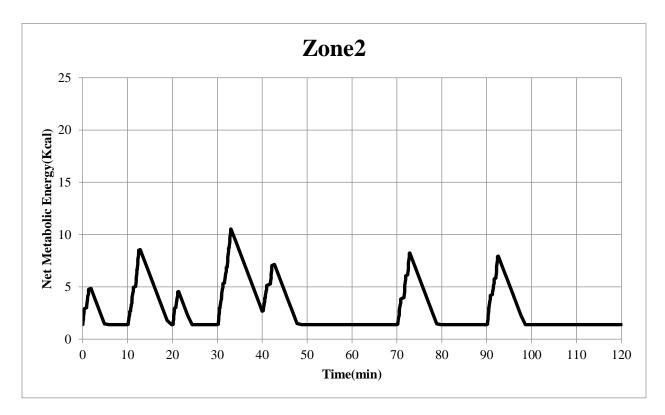


Figure 10: Net Metabolic Energy vs Time graph for Zone2 operator including resting energy recovery

#### **Conclusions and Recommendations**

In this study, we used the Garg energy expenditure prediction model [13] for manual material handlings activities to calculate the same for tugger operators in manufacturing environments. To automate the calculation process, we created an excel-based VBA program that would import the tugger routes information data generated through Proplanner - Flow Planner. The program would then calculate the individual and cumulative energy expenditure values for the tugger operators' activities and will also populate the energy vs time graph for the entire work duration.

After incorporating resting periods into the study for the time durations when the tugger operator is idle, the resulting net metabolic energy expenditure vs time graph showed the energy peaks and dips during the work period. This visualization of the operator's energy expenditure over time can help manufacturing engineers assess the material handling jobs and make necessary ergonomic improvements for the tugger operators.

This is a first initiative of calculating energy expenditures of operator by using the task details information obtained from a material handling automation software. Hence, for some of the field values like the operator's gender, body weight, the start and end heights for lifting activities, the industrial standard averages were used. Currently this program resides outside the Flow Planner module as separate excel program. Moving forward, this model can be programmed into the Flow Planner's Tugger module where the users can specify the load parameters and the exact biometrics of the tugger operators which can significantly improve the fidelity of this program.

Flow Planner's algorithm for calculating the tugger routes currently has two main constraints – minimize time for delivery and maximize capacity utilization of the tugger carts.

On integrating this program into Flow Planner, ergonomic constraints can also be added to the algorithm using both the cumulative energy expenditure analysis and the net metabolic energy analysis. The cumulative energy expenditure analysis provides information on the energy expenditure accumulation of the operator throughout the work shift period. After further research on the industrial standards, a limiting value for the acceptable energy expenditure per work shift period can be defined and used as an ergonomic constraint. Also, the net metabolic energy expenditure analysis provides information about the energy peaks during the work shift period. This could also be used as a constraint by defining a maximum acceptable and average net metabolic energy values though further research, and limiting the energy fluctuations to stay between this maximum and average net metabolic energy expenditure values.

Until the time when the entire material handling within a manufacturing setting is completely taken over by AGVs and robots, there will be some level of manual material handling involved in production facilities. This model can be mimicked for any other material handling methods alternatives that are currently existing or may be developed in the upcoming years and for any production environment.

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# Appendix

The following are the additional screen-prints of the Proplanner – Flow Planner tugger route analysis and the automated energy expenditure assessment program that was created as part of this study.

							P1						<u>+</u>	<u> </u>	· · ·		ZONE2_STAGE
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DRILL	Part	%	From	Method	(C)ontainer	C/Trip	Parts/C	To Loc	v	ia Loc Via N	lethod	Via C/Trip	Description		File Ope	n	
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	235448	100.00	REC_2	ZONE1	FLAT	2.0	-1.0	REC_14				0.0	235448		Save As		
	235449	100.00	REC_14	ZONE1	FLAT	1.0	-1.0	_				0.0	235449				ASSEMILY
	111332		_	ZONE1	CRATE2	1.0		REC_4				0.0	111332		New (Clea	r)	
	RETURN		-	ZONE1	!NA	1.0		STAGE				0.0					╎╺╗┢┋┊
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-GREAS	111332	100.00	P2	ZONE1	CRATE2	1.0	-1.0	BORE				0.0	111332			_	
	111456	100.00	BORE	ZONE1	BOX35	1.0	-2.0	HOLEPUI	ICH			0.0	111456		Insert Ro	w	
	235448	100.00	HOLEPUNCH	ZONE1	FLAT	2.0	-2.0	DE-GREA	SING			0.0	235448			_	0 Ψ <b> </b>
	235449	100.00	DE-GREASING	ZONE1	FLAT	1.0	-2.0	METAL-F	ORMING			0.0	235449		Remove R	ow	
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Figure 11: Flow Planner Part Routings tab of the sample tugger analysis

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	BOX36 BOX42	14.00 23.00	22.00 15.00		1	1		1	BOX BOX									
	CRATE2	36.00	36.00		1	1		1	CRATE									1
♥❤⊿	CRATE3	42.00	36.00		1	1		1	CRATE									
	CRATE4	26.00	28.00		1	1		1	CRATE									
	CRATE5	48.00	56.00	48.00	1	1		1	CRATE									
	FLAT	48.00	48.00	48.00	1	1		1	CRATE									1
<u>)</u>							s	Stack H	eight									
<u> </u>	Container ID	Lengt	th (in)	Width (in)	Height	(in)	Full Qty	/	Empty Qt	у	Color		Group					
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Figure 12: Flow Planner Containers tab of the sample tugger analysis

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All None	
IRILL Method Calc Qty Type Load (secs) Unload (secs) Start Loc Color	
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ZUREZ TES 1.00 10G 15 15 START 2	ASSEM SEEM 31
Method Load UnLoad Type Process Process Start Loc	
	Color Update Add Remove
Method Types	
Type     Qty     Eff. %     Max (min)     Fixed\$     Variable\$     Straight Speed (f/s)     AcceVDecel (f/s^2)     Turn Angle (deg)     Alsle Path Lay       TUG     2.00     100     115200     0     20     5     120     PF_AISLEPAT	
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(FUsec <sup>4</sup> (FUsec <sup>2</sup> )	
Method (rusec) 2 / Aisle Type Eff Minutes Speed Accel / Turn Path Name Qty % per Year Fixed S S/Hour Decel Angle Layer Color	
CUSTOMER SE     TUG     2.00     100     115200     0     20     5     5     120     PF_4     #Ref     Update     Add	Remove
	Import Methods Save Methods
	Help Goto AutoCAD RACK RACK

Figure 13: Flow Planner Methods tab of the sample tugger analysis

									P1					C 338EC 4 F	FC 5			ZÜNE
	A Propla	inner FlowP	anner (5.4.2.0)											Bar Toke I	inite-Y mare		X	
	Part Routin	gs Products	Locations F	Paths	Methods	Processes	Containers	Filter	Freq/Congest	Utilization	Tuggers	Reports	Settings					
10	Process	Time (sec)	Time (MOD/TM	U) Act	tivity			Weight	SC									E
_	UNLOAD		0			RATE) CF(1	5/9/I/BOX)	0	0									-
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H	UNLOAD	-1			CX(15/15/	VCRATE) CF	(15/9/VBOX)	)				0	0	date Add	Rem	ove		ŁĻ
					Activity Pa	arsing Ter	mplate			$\sim$								
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Figure 14: Flow Planner Processes tab of the sample tugger analysis

	HOLE-PUNC		"HAN II II	HAND F	INISHIN			METAL CUTT	ING	<u>00</u>		21			REBOSE	EBCQSE			GR <sup>EY</sup> RACK	RACK	RECEIVING2		
2	╶─┝┝╴╥╦╗╴╴╶┤		7	 i m				P1						+	REC 33	REC 4 R	5. 5.ck- 5 pa	CK RAG	CK RACK	RACK	ZUNE2_STAGE	=	NAT NAN
				owPlanner		s Metho	ds Proc	esses Containers	Filter	Freq/Con	gest U	Itiliza	ation Tu	ggers Reports	Settings					×	 		
		· ·	t Deliverie	_	Status:	Done.														Ŧ			ASS
1 1999 - L	DRILL	Step	1: Import D	eliveries									Step 2:Lo	ocation Route Gro	oups							Ħ 🗐	- C`
_ الصلح	$\langle \mathcal{P} \rangle \langle \mathcal{Q} \rangle$	D	Part	Container	Cont. Qty	From	Stage	То	ETD		Dir ^		Route	Interval (mins)	Include	Path	Volume	Eff%	Stage		i 🕷 👝 🖌	<b>4</b>	
	~~~~~ <u>~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~</u>	1	111456	BOX35	1	REC_2	STAGE	HOLEPUNCH	7.1		1		ZONE1	7.0/15.0/10/10	YES	*T/P1/P2	300	100				┛	
- i		2	111847	BOX36	1	REC_3	STAGE	DE-BURING		/10/2/.5)	1		ZONE2	7.0/15.0/10/10	YES		300	100	ZONE2_		ASSEMBL	EMBLY	
3		3	111332	CRATE2	1	REC_4	STAGE	BORE	7.1		-1										ASSEMBLY		
		4	111445	CRATE2	1	REC_5	STAGE	DE-BURING1		/10/1/1)	-1										•••¶ (	ЦШ	3
		5	235448	FLAT	2	REC_14	STAGE	DE-GREASING	7.1 7.1		1												
		6		FLAT	1	REC_15 REC_16	STAGE STAGE	METAL-FORMING METAL-STAMPING	7.7		1										i r	┡	1000
1 🗐 ; 🛛 👬 👬	=GREAS <mark>:  </mark> "  🛔	8	235450	BOX35	1	REC_10 REC_17	STAGE	HOLEPUNCH	8.2												l i		
<u> </u>		9	111847	BOX35	2	REC_10	STAGE	DE-BURING	8.1														
		10	111332	CRATE2	1	REC_11	STAGE		8.7		1		<						>	x.		7	
<u>200</u>		11	111445	CRATE2	1	REC_12	STAGE	DE-BURING1	8		1		Route	01-15-	d/Intv/Tot	Includ	4.	Path			i		
200		12	235448	FLAT	1	REC_13	STAGE	DE-GREASING	8.8		-1		ZONE				*T/P1/P				!		
		13	235449	FLAT	2	REC_30	STAGE	METAL-FORMING	8.9		1		ZUNE	1 7.0/15.0	10/10		-1/P1/P	2			L	=	
	PURCHASING	14	235450	FLAT	1	REC_31	STAGE	METAL-STAMPING	8.7		1		Volume	300	Ft*3	V. Eff%	100				r		
		š	005000						~ 7		>		Staging	Area								a 🗏 🛙	
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								Straight Flow	-						1								
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Figure 15: Flow Planner Tuggers tab of the sample tugger analysis

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Containers Gonzaliners Gonzaliners	L
PURCHASING	
	PACKATING
CUSTOMER :	
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DESIGN	RACK RACK RACK
	RACK RACK RACK

Figure 16: Flow Planner Settings tab of the sample tugger analysis

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*Figure 17: Sheet1 of the automated energy expenditure calculation program created* 

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ZONE1107.0000		111456.00		STAGE	ZONE1	BOX35	1.00		REC 2				111456.00	(/	()	- (,	(	414.00	414.00			6.90	0.00	0.00 0		0.00		2.83	3
ZONE1 07.0000		235448.00			ZONE1	FLAT	2.00		REC 14				235448.00	15.00	10.00			114.00	114.00			1.90	0.00	0.00 0			128	3.63	
ZONE1 07.0000		235449.00		_	ZONE1	FLAT	1.00		REC 15				235449.00					86.00	86.00			1.43	0.00	0.00 0			64		
ZONE1107.0000		111332.00			ZONE1	CRATE2	1.00		REC 4				111332.00					576.00	576.00			9.60	0.00	0.00 0			-27		
ZONE1 07.0000		RETURN	100.00 F		ZONE1	INA	1.00		STAGE			0.00						362.00	362.00		3.37	6.03	0.00	0.00 0				-11.63	
ZONE1 07.0000		TRAVEL	100.00 5		ZONE1	INA	1.00					0.00						794.00	794.00				0.00	0.00 0					
ZONE1 07.0000		111456.00			ZONE1	BOX35	1.00		HOLEPU	NCH			111456.00					808.00	808.00				0.00	0.00 0					
ZONE1:07.0000		111332.00				CRATE2			BORE				111332.00					391.00	391.00			6.52	0.00	0.00 0					
ZONE1 07.0000		TRAVEL	100.00 8		ZONE1	INA	1.00					0.00						0.00	0.00			0.00	0.00	0.00 0					
ZONE1 07.0000		235448.00			ZONE1	FLAT	2.00		DE-GREA	SING			235448.00	15.00	10.00			1377.00	1377.00				0.00	0.00 0			-128	8.23	
ZONE1 07.0000		235449.00				FLAT	1.00		METAL-F		uc.		235449.00	10.00	10.00			218.00	218.00			3.63	0.00	0.00 0			-64	29.60	
ZONE1 07.0000		RETURN		METAL-FO		INA	1.00		STAGE	Citivin	10	0.00						1902.00	1902.00		5.13	31.70	0.00	0.00 0					
ZONE1 07.1000		111847.00			ZONE1	BOX36	1.00		REC 3				111847.00					530.00	530.00			8.83	0.00	0.00 0					
ZONE1 07.1000		RETURN	100.00 F		ZONE1	INA	1.00		STAGE			0.00						530.00	530.00		2.43	8.83	0.00	0.00 0					
ZONE1 07.1000		TRAVEL	100.00 5		ZONE1	INA	1.00					0.00						794.00	794.00		4.53		0.00	0.00 0				-10.47	
ZONE1 07.1000		111847.00			ZONE1	BOX36	1.00		DE-BURI	NG		0.00						1022.00	1022.00			17.03	0.00	0.00 0					
ZONE1 07.1000		TRAVEL		DE-BURIN		INA	1.00					0.00						177.00	177.00		6.90	2.95	0.00	0.00 0					
ZONE1 07.1000		RETURN	100.00		ZONE1	INA	1.00		STAGE			0.00						2329.00	2329.00		3.77		0.00	0.00 0					
ZONE1 07.3000		111445.00			ZONE1	CRATE2	1.00		REC 5				111445.00					471.00	471.00			7.85	0.00	0.00 0					
ZONE1 07.3000		RETURN	100.00 F		ZONE1	INA	1.00		STAGE			0.00						471.00	471.00		3.37	7.85	0.00	0.00 0					
ZONE1 07.3000		TRAVEL	100.00 5		ZONE1	INA	1.00					0.00						794.00	794.00		4.53		0.00	0.00 0					
ZONE1 07.3000		TRAVEL	100.00 8		ZONE1	INA	1.00					0.00						1199.00	1199.00				0.00	0.00 0					
ZONE1 07.3000		111445.00			ZONE1 ZONE1	CRATE2			DE-BURI	NG1			111445.00					0.00	0.00			0.00	0.00	0.00 0				-4.57	
ZONE1 07.3000		RETURN		DE-BURIN		INA	1.00		STAGE			0.00						2536.00	2536.00		4.40	42.27	0.00	0.00 0				-10.60	
ZONE1 07.4000		235450.00			ZONE1	FLAT	1.00		REC 16				235450.00					114.00	114.00			1.90	0.00	0.00 0					
ZONE1 07.4000 ZONE1 07.4000		235988.00			ZONE1 ZONE1	FLAT	1.00		REC_10 REC_17				235988.00					18.00	18.00			0.30	0.00	0.00 0				3.93	
ZONE1 07.4000 ZONE1 07.4000		RETURN	100.00 F		ZONE1	INA	1.00		STAGE			0.00						132.00	132.00		3.00	2.20	0.00	0.00 0				-12.00	
ZONE1 07.4000		TRAVEL	100.00 5		ZONE1	INA	1.00					0.00						794.00	794.00		4.53		0.00	0.00 0					
ZONE1 07.4000		235988.00			ZONE1 ZONE1	FLAT	1.00		METALC	ITTING			235988.00					0.00	0.00			0.00	0.00	0.00 0			-64		
ZONE1 07.4000 ZONE1 07.4000		TRAVEL		METALCU		INA	1.00			51 HING		0.00						1199.00	1199.00		9.17		0.00	0.00 0					
ZONE1 07.4000 ZONE1 07.4000		235450.00			ZONE1	FLAT	1.00		METAL-S	TAMP	ING	0.00						2586.00	2586.00				0.00	0.00 0			-64		
ZONE1 07.4000 ZONE1 07.4000		235450.00 RETURN		PZ METAL-SI		INA	1.00		STAGE	AWP		0.00							1069.00		6.41		0.00	0.00 0					
ZONE1 07.5000		235989.00			ZONE1	FLAT	1.00		REC 26				235989.00					691.00				11.52	0.00	0.00 0			64	2.83	
		233383.00	100.00 5	JUAGE	2UNE1	FLAT	1.00	-1.00	nct 20			0.00	∠33383.00						00.160		17.63	11.52	0.00	0.00 0	uu U.UU	0.00	04	2.83	2

Figure 18: Sheet2 of the automated energy expenditure calculation program created

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7.0		STAGE	REC_2							0.12		0.12		1.35												
	Climb Down			1.00		10.00 0.00					0.13	0.12		1.48												
	Walking to shelf			1.00	0.00			4.53			0.07	0.13		1.55												
	Lift part from shelf			1.00		10.00 35.00					0.31	0.26		1.86								1				
	Carry part to tugger-ba	ick		1.00	0.00		25.00	4.53			0.09	0.28		1.95						Zo	ne1					
	Lower part on tugger			1.00		35.00 15.00	25.00				0.15	0.40		2.10												
	Walking to tugger-from	nt		1.00	0.00			2.26			0.03	0.41		2.13		20.00										
	Climb Up			1.00		0.00 10.00					0.34	0.41		2.47		18.00	+						A A			
	Drive	REC_2	REC_14							0.03	0.01	0.44		2.48		16.00										
	Climb Down			1.00		10.00 0.00					0.13	0.44		2.61									$(\Lambda T)$			
	Walking to shelf			1.00	0.00			5.81			0.08	0.47		2.69		14.00	111						141			
	Lift part from shelf			1.00		10.00 35.00					0.31	0.59		3.00		<b>〒</b> 12.00	+++11						1			
	Carry part to tugger-ba	ick		1.00	0.00		25.00	5.81		0.02		0.62		3.12		3	1 1 1						1	1		
	Lower part on tugger			1.00		35.00 15.00	25.00				0.15	0.74		3.27		Å 10.00	1	1	Ν	1			1	1		
	Walking to tugger-from	nt		1.00	0.00			2.90			0.04	0.75		3.31		.00 g		1	A				1			
	Climb Up			1.00		0.00 10.00					0.34	0.75		3.65			1	1	- 71		1		1			
	Drive	REC_14	REC_15							0.02		0.78		3.65		6.00	1			A	1 1	٨				
	Climb Down			1.00		10.00 0.00					0.13	0.78		3.78		4.00	+		$\wedge + $	$(\Lambda)$	111					
	Walking to shelf			1.00	0.00			5.76			0.08	0.80		3.86		2.00	1			VII	V \	- 11				
	Lift part from shelf			1.00		10.00 35.00				0.13		0.93		4.17					0	• •						
	Carry part to tugger-ba	ick		1.00	0.00		25.00	5.76			0.12	0.95		4.29		0.00										
	Lower part on tugger			1.00		35.00 15.00	25.00				0.15	1.08		9,44			0.00	20.00	40.00	60.00	80.00	100	.00 1	20.00	140.00	
	Walking to tugger-from	nt		1.00	0.00			2.88		0.01		1.09		4.48							lime(min)					
	Climb Up			1.00		0.00 10.00					0.34	1.09		4.82												
	Drive	REC_15	REC_4							0.16		1.25		4.85												
	Climb Down			1.00		10.00 0.00					0.13	1.25		4.98												
	Walking to tugger-bac	:k		1.00	0.00			19.44			0.28	1.33		5.26												
	Lift part from tugger			1.00		15.00 35.00					0.24	1.41		5.50												
	Carry part to Shelf			1.00	0.00			38.88			0.79	1.57		5.29												
	Lower part on Shelf			1.00		35.00 10.00	25.00				0.20	1.66		5.49												
	Walking to tugger			1.00	0.00			38.88			0.57	1.82		7.06												
	Climb Up			1.00		0.00 10.00					0.34	1.82		7.40												
	Drive			1.00							0.02	1.92		7.42												
		STAGE		1.00							0.04	2.14		7.46												
		P1	HOLEPI								0.04	2.37		7.50												
	Climb Down			1.00		10.00 0.00					0.13	2.37		7.63												
	Walking to tugger-bac	:k		1.00	0.00			21.02			0.31	2.45		7.94												
	Lift part from tugger			1.00		15.00 35.00					0.24	2.54		8.18												
	Carry part to Shelf			1.00	0.00		25.00	42.03		0.18	0.86	2.71		9.04												
	Lower part on Shelf			1.00		35.00 10.00	25.00			0.08	0.20	2.79		9.24												
	Walking to tugger			1.00	0.00			42.03		0.18	0.61	2.97		9.85												
	Commands Data						- 1	(+								_										
				penditure		ergyExpendit																				

Figure 19: Sheet3 of the automated energy expenditure calculation program created