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.

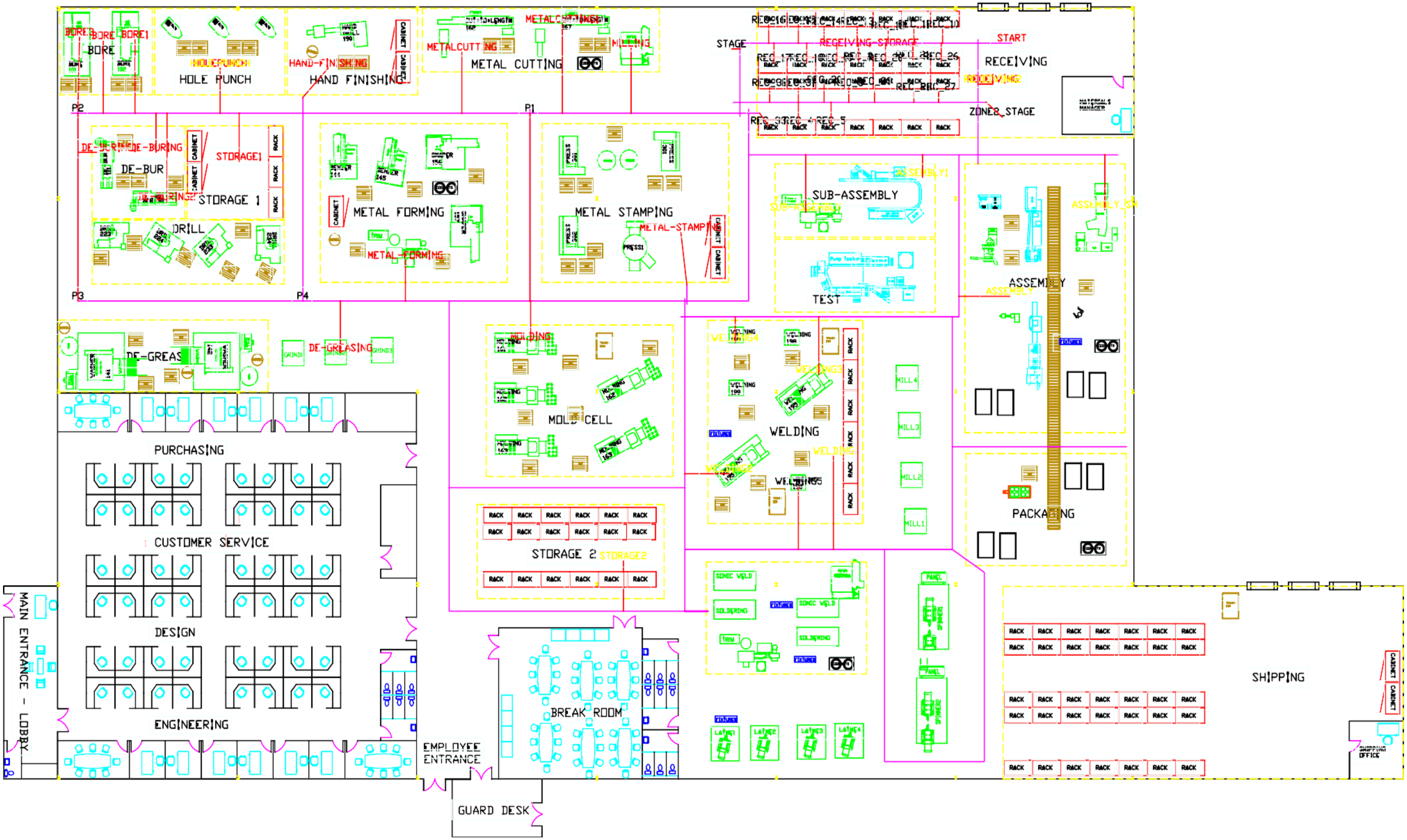
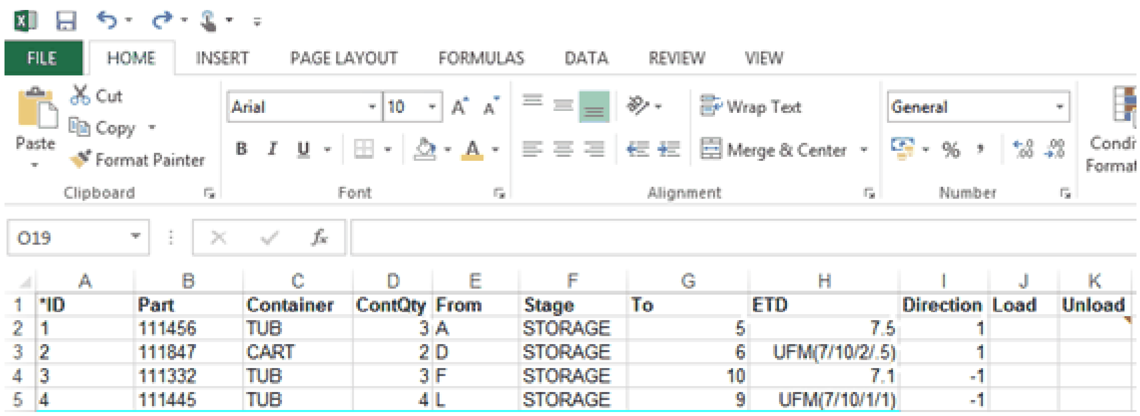


Figure1: AutoCAD factory layout

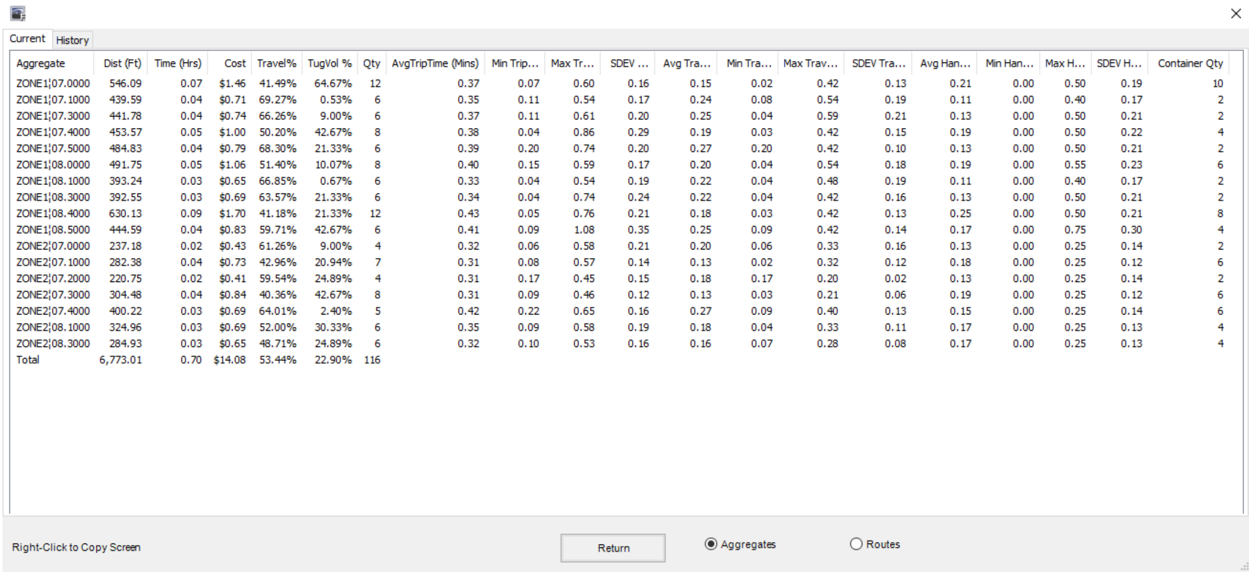


*ID	Part	Container	ContQty	From	Stage	To	ETD	Direction	Load	Unload
1	111456	TUB	3	A	STORAGE	5	7.5	1		
2	111847	CART	2	D	STORAGE	6	UFM(7/10/2/.5)	1		
3	111332	TUB	3	F	STORAGE	10	7.1	-1		
4	111445	TUB	4	L	STORAGE	9	UFM(7/10/1/1)	-1		

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

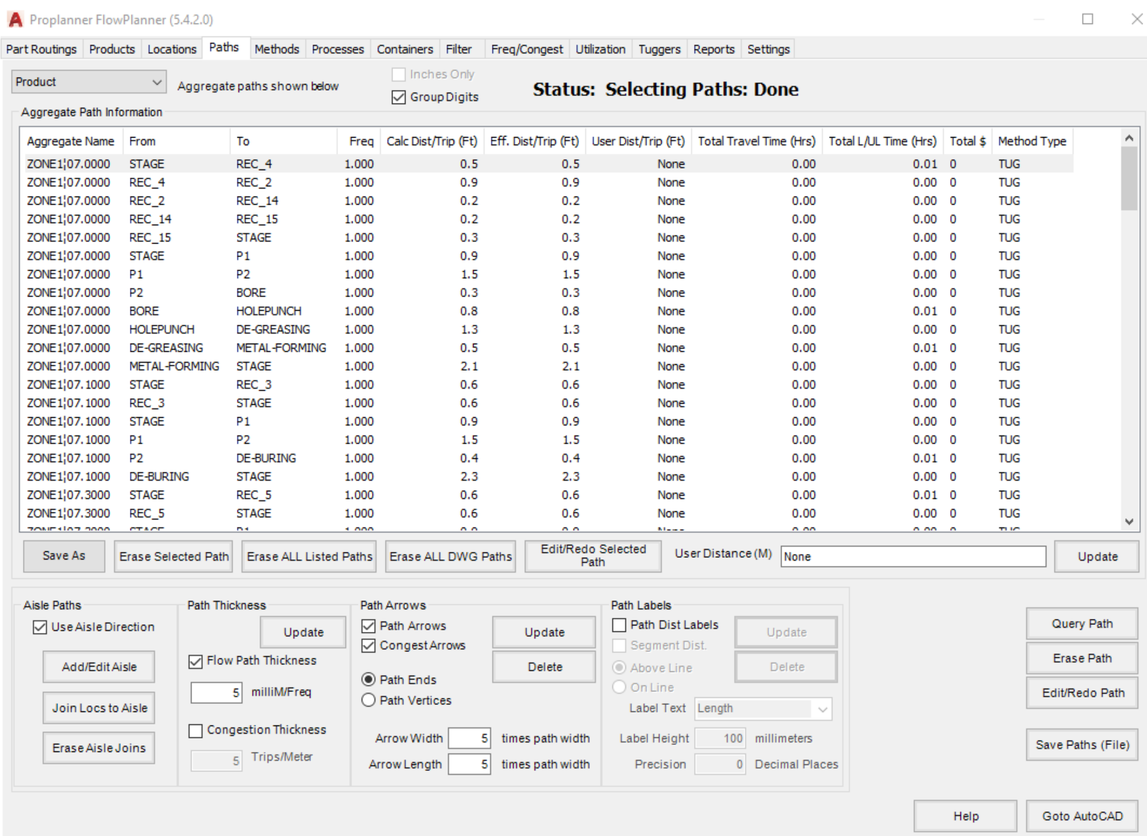
After the route file is loaded, the user can select the type of flow, Straight Flow or Aisle Flow, for generating the tugger routes. Straight Flow will show the tugger routes mapped based on the shortest path possible which may not be the practical case. Aisle Flow will populate the tugger routes with 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.

Figure 3: Flow Planner Tugger route results



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													

Figure 4: Flow Planner Tugger route statistics



Aggregate Name	From	To	Freq	Calc Dist/Trip (Ft)	Eff. Dist/Trip (Ft)	User Dist/Trip (Ft)	Total Travel Time (Hrs)	Total L/UL Time (Hrs)	Total $	Method Type
ZONE1¦07.0000	STAGE	REC_4	1.000	0.5	0.5	None	0.00	0.01	0	TUG
ZONE1¦07.0000	REC_4	REC_2	1.000	0.9	0.9	None	0.00	0.00	0	TUG
ZONE1¦07.0000	REC_2	REC_14	1.000	0.2	0.2	None	0.00	0.00	0	TUG
ZONE1¦07.0000	REC_14	REC_15	1.000	0.2	0.2	None	0.00	0.00	0	TUG
ZONE1¦07.0000	REC_15	STAGE	1.000	0.3	0.3	None	0.00	0.00	0	TUG
ZONE1¦07.0000	STAGE	P1	1.000	0.9	0.9	None	0.00	0.00	0	TUG
ZONE1¦07.0000	P1	P2	1.000	1.5	1.5	None	0.00	0.00	0	TUG
ZONE1¦07.0000	P2	BORE	1.000	0.3	0.3	None	0.00	0.00	0	TUG
ZONE1¦07.0000	BORE	HOLEPUNCH	1.000	0.8	0.8	None	0.00	0.01	0	TUG
ZONE1¦07.0000	HOLEPUNCH	DE-GREASING	1.000	1.3	1.3	None	0.00	0.00	0	TUG
ZONE1¦07.0000	DE-GREASING	METAL-FORMING	1.000	0.5	0.5	None	0.00	0.01	0	TUG
ZONE1¦07.0000	METAL-FORMING	STAGE	1.000	2.1	2.1	None	0.00	0.00	0	TUG
ZONE1¦07.1000	STAGE	REC_3	1.000	0.6	0.6	None	0.00	0.00	0	TUG
ZONE1¦07.1000	REC_3	STAGE	1.000	0.6	0.6	None	0.00	0.00	0	TUG
ZONE1¦07.1000	STAGE	P1	1.000	0.9	0.9	None	0.00	0.00	0	TUG
ZONE1¦07.1000	P1	P2	1.000	1.5	1.5	None	0.00	0.00	0	TUG
ZONE1¦07.1000	P2	DE-BURING	1.000	0.4	0.4	None	0.00	0.01	0	TUG
ZONE1¦07.1000	DE-BURING	STAGE	1.000	2.3	2.3	None	0.00	0.00	0	TUG
ZONE1¦07.3000	STAGE	REC_5	1.000	0.6	0.6	None	0.00	0.01	0	TUG
ZONE1¦07.3000	REC_5	STAGE	1.000	0.6	0.6	None	0.00	0.00	0	TUG

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,

$\overline{E_{Job}}$ = Average energy expenditure rate of the job (Kcal/min)

$E_{posture}$ = Metabolic energy expenditure rate due to maintenance of i^{th} of the job (Kcal/min)

t_i = Time duration for the i^{th} posture (min)

n_p = Total number of body postures employed in the job

ΔE_{task_i} = Net metabolic energy expenditure of the i^{th} task in steady state (Kcal)

n = Total number of tasks in the given job

T = 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,

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

Carrying loads held against thighs or waist,

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

Stoop Lift,

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

Stoop Lower,

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

Climb up,

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

Climb down,

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

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.

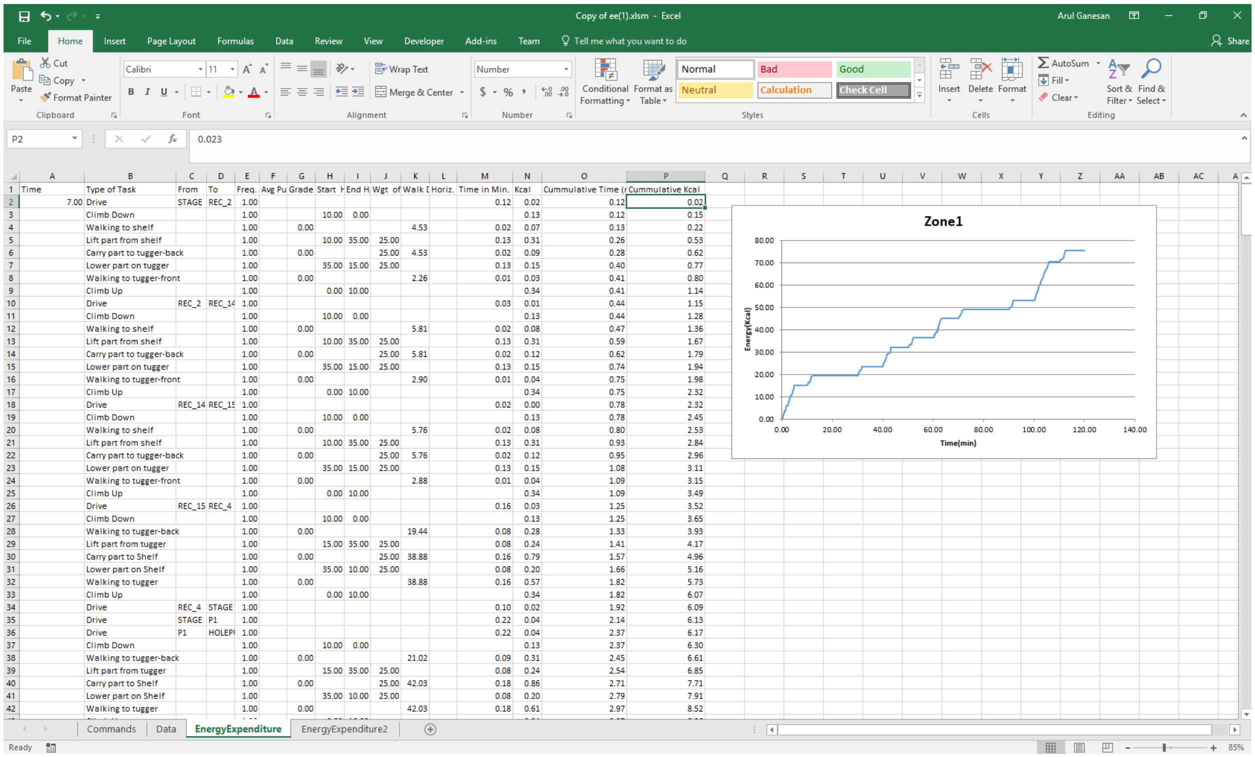


Figure 6: Sample results from the automated energy expenditure caculaton program

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.	Route Interval	Route completion 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.

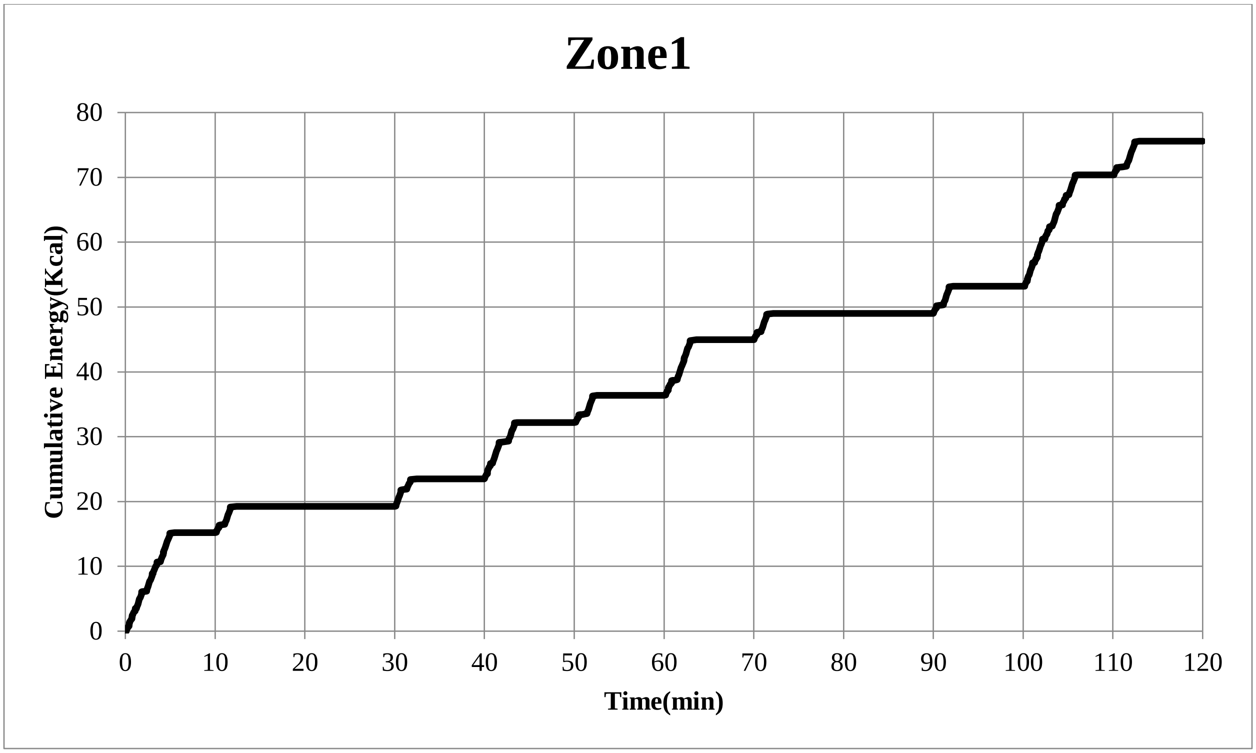


Figure 7: Cumulative Energy vs Time graph for Zone1 operator

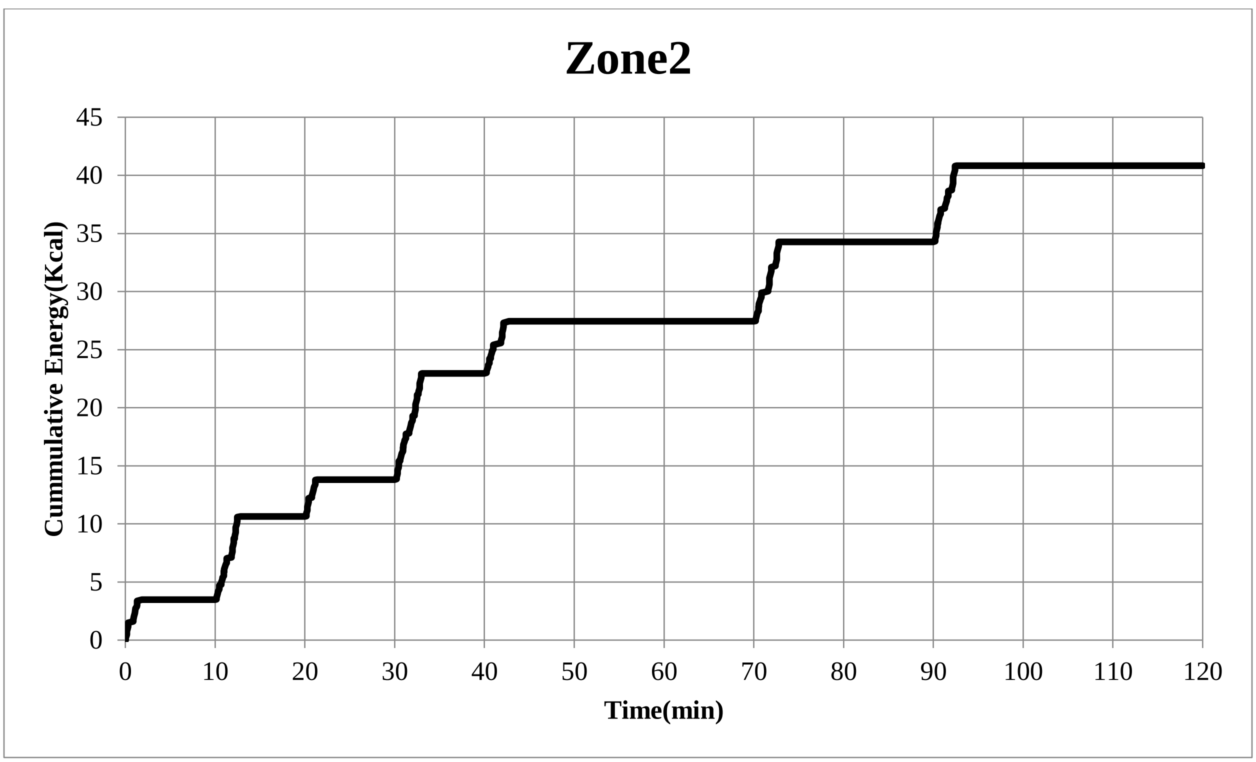


Figure 8: Cumulative Energy vs Time graph for Zone2 operator

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,

ΔE = Net metabolic energy expenditure (Kcal)

E_{task} = Total steady state metabolic energy expenditure (Kcal)

E_{rest} = 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,

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

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.

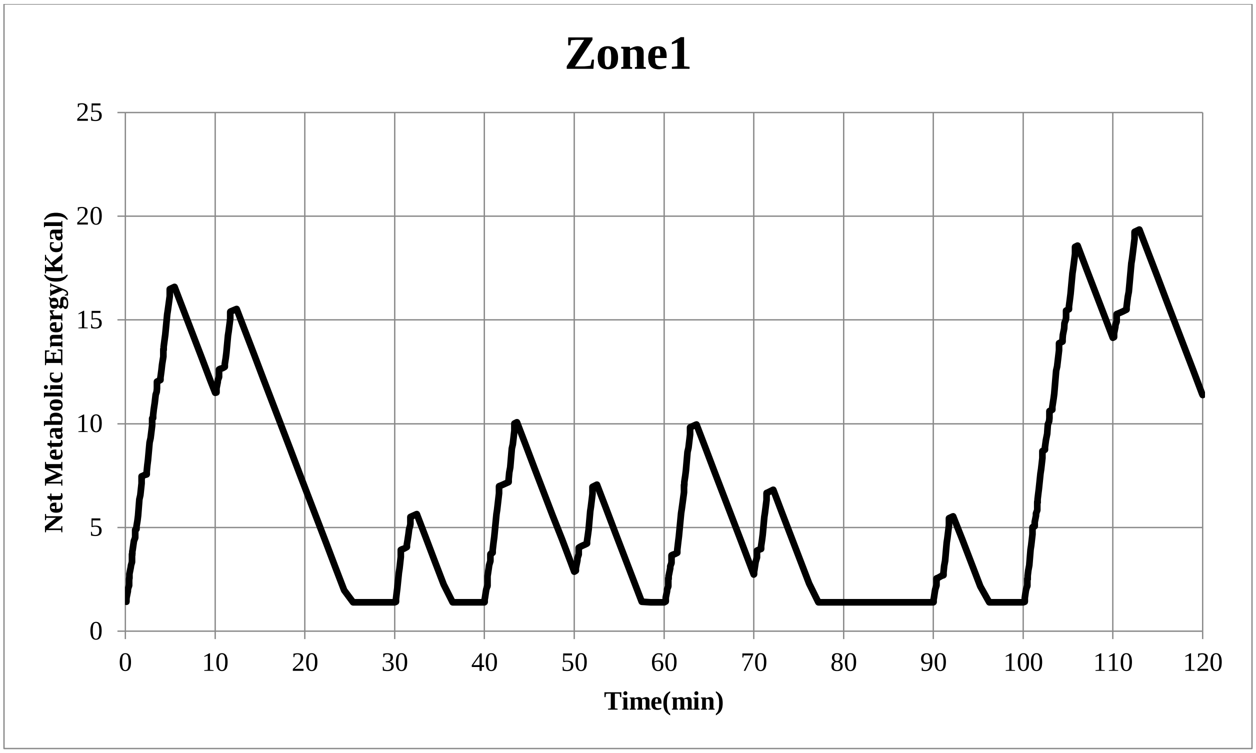


Figure 9: Net Metabolic Energy vs Time graph for Zone1 operator including resting energy recovery

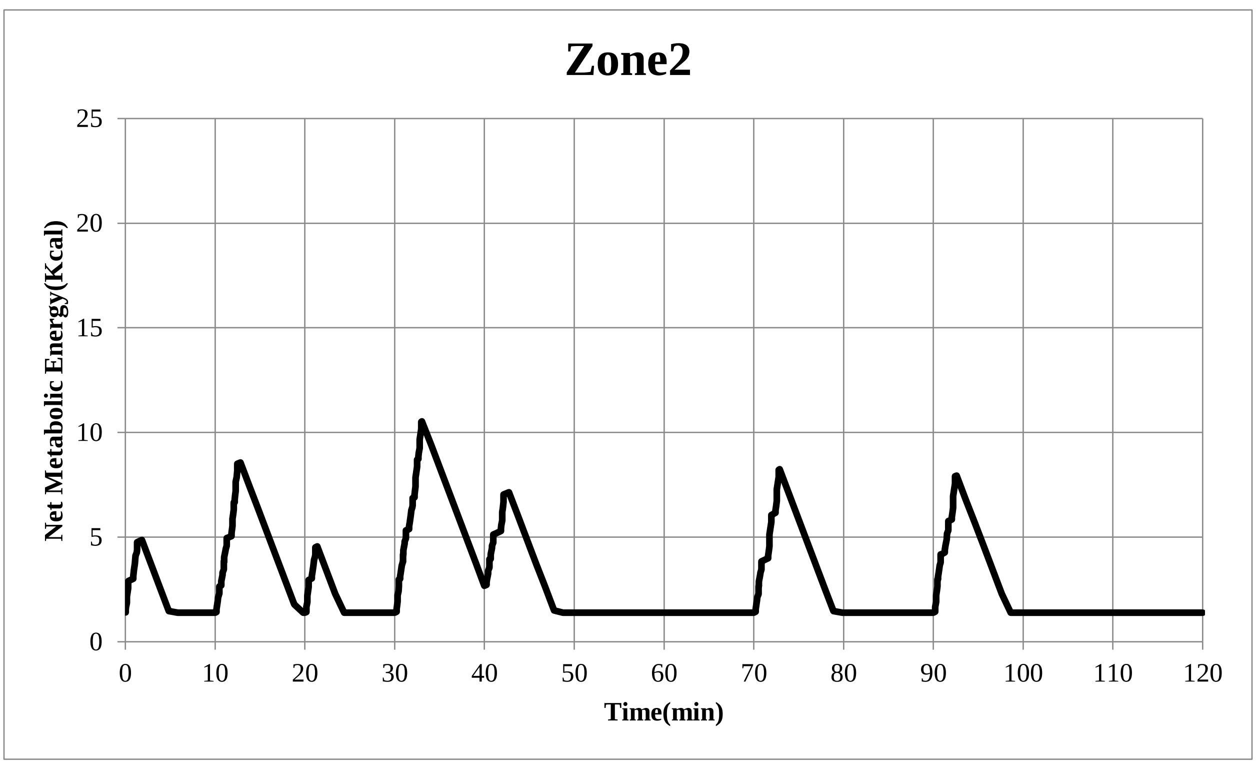


Figure 10: Net Metabolic Energy vs Time graph for Zone2 operator including resting energy recovery

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.

References

[1] H. Dos, R. Leite, and G. E. Vieira, “Lean philosophy and its applications in the service industry: a review of the current knowledge,” *Production*, 2015.

[2] C. B. Choi, P. Park, Y. H. Kim, M. Susan Hallbeck, and M. C. Jung, “Comparison of visibility measurement techniques for forklift truck design factors,” *Appl. Ergon.*, vol. 40, no. 2, pp. 280–285, 2009.

[3] F. Facchini, G. Mummolo, G. Mossa, S. Digiesi, F. Boenzi, and R. Verriello, “Minimizing the carbon footprint of material handling equipment: Comparison of electric and LPG forklifts,” *J. Ind. Eng. Manag.*, vol. 9, no. 5, pp. 1035–1046, 2016.

[4] X. Ge, Y. Jin, and C. Zhu, “Analysis and optimization of forklift truck steering wheel idle vibration,” *J. Adv. Mech. Des. Syst. Manuf.*, vol. 9, no. 3, pp. JAMDSM0023-JAMDSM0023, 2015.

[5] E. Hosseinzadeh, M. Rokni, S. G. Advani, and A. K. Prasad, “Performance simulation and analysis of a fuel cell/battery hybrid forklift truck,” *Int. J. Hydrogen Energy*, vol. 38, no. 11, pp. 4241–4249, 2013.

[6] J. Hoy *et al.*, “Whole body vibration and posture as risk factors for low back pain among forklift truck drivers,” *J. Sound Vib.*, vol. 284, no. 3–5, pp. 933–946, 2005.

[7] K. K. Yuen, S. H. Choi, and X. B. Yang, “A full-immersive CAVE-based VR simulation system of forklift truck operations for safety training,” *Comput. Aided. Des. Appl.*, vol. 7, no. 2, pp. 235–245, 2010.

[8] T. J. Larsson and G. Rechnitzer, “Forklift trucks-analysis of severe and fatal occupational injuries, critical incidents and priorities for prevention,” *Saf. Sci.*, vol. 17, no. 4, pp. 275–289, 1994.

[9] N. Stout-Wiegand, “Characteristics of work-related injuries involving forklift trucks,” *J. Safety Res.*, vol. 18, no. 4, pp. 179–190, 1987.

[10] M. Mashaei and B. Lennartson, “A universal framework for lean design and control of automated material handling systems,” in *IEEE International Conference on Emerging Technologies and Factory Automation, ETFA*, 2012.

[11] T. K. Acharya, “Material Handling and Process Improvement Using Lean Manufacturing Principles,” *Int. J. Ind. Eng.*, vol. 18, no. 7, pp. 357–368, 2011.

[12] N. M. Nur, S. Z. M. Dawal, M. Dahari, and J. Sanusi, “The effects of energy expenditure rate on work productivity performance at different levels of production standard time,” *J. Phys. Ther. Sci.*, 2015.

[13] A. Garg, D. B. Chaffin, and G. D. Herrin, “Prediction Of Metabolic Rates For Manual Materials Handling Jobs,” *Am. Ind. Hyg. Assoc. J.*, 1978.

[14] M. Jetté, K. Sidney, and G. Blümchen, “Metabolic equivalents (METS) in exercise testing, exercise prescription, and evaluation of functional capacity,” *Clin. Cardiol.*, vol. 13, no. 8, pp. 555–565, 1990.

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.

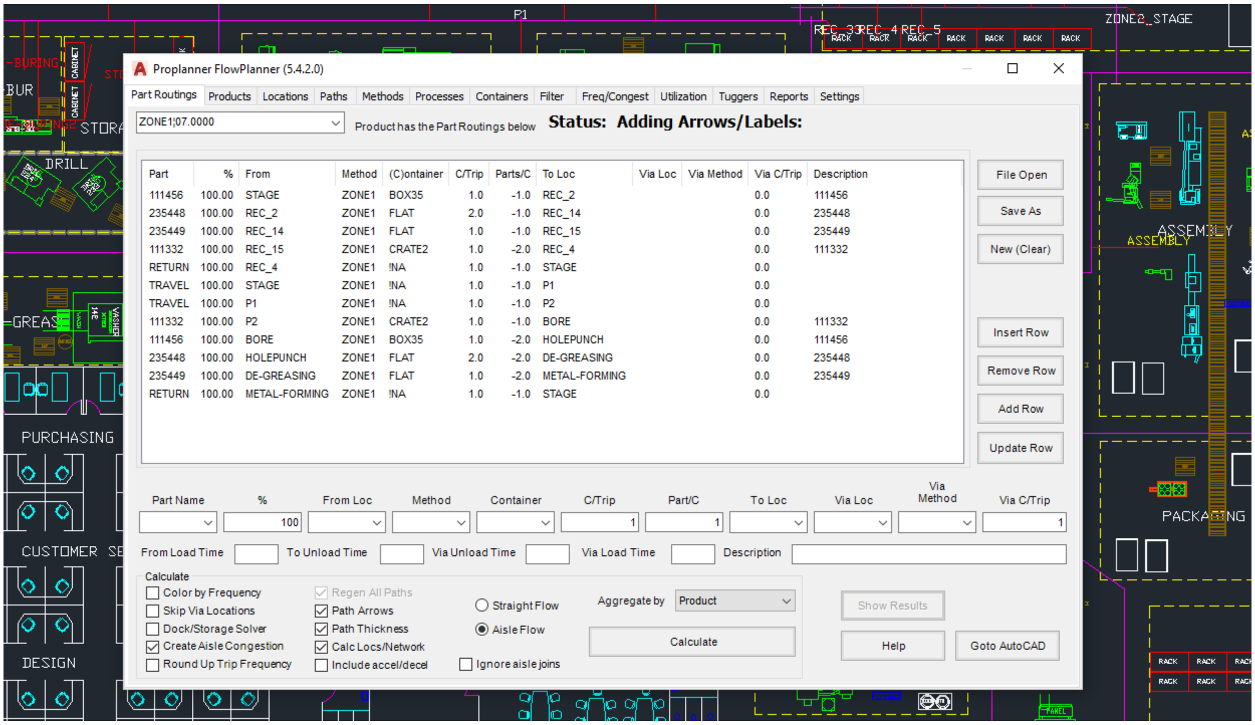


Figure 11: Flow Planner Part Routings tab of the sample tugger analysis

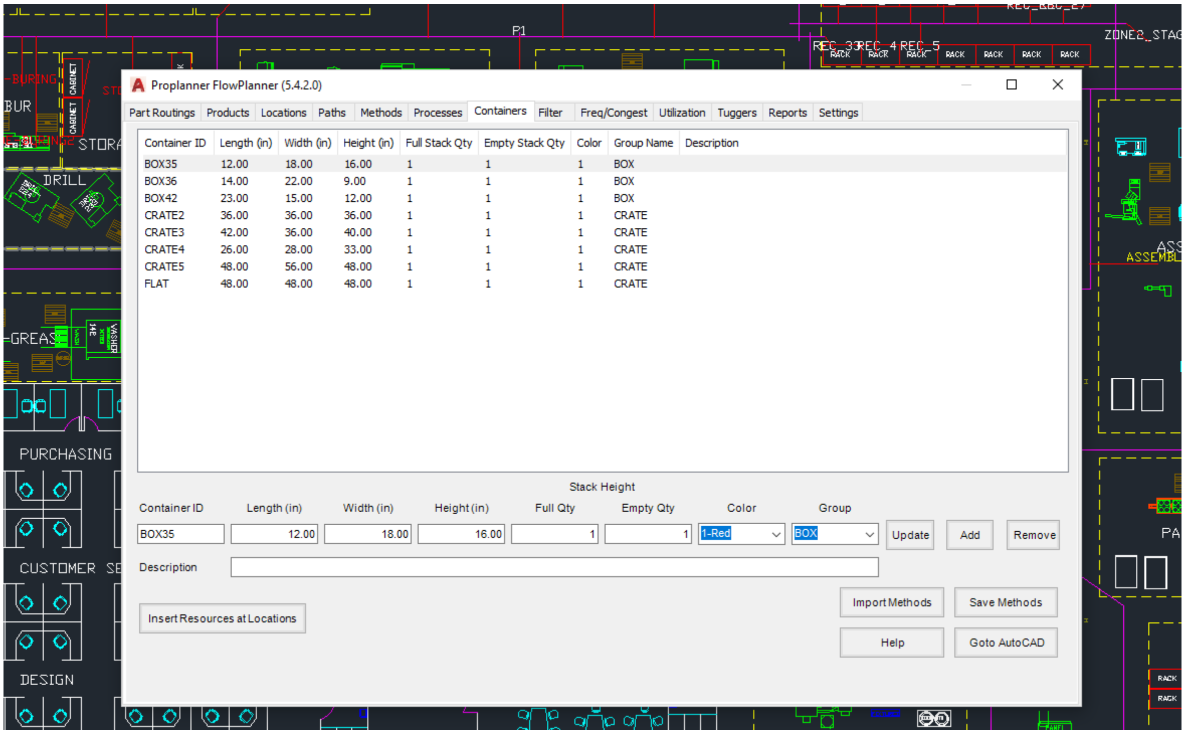


Figure 12: Flow Planner Containers tab of the sample tugger analysis

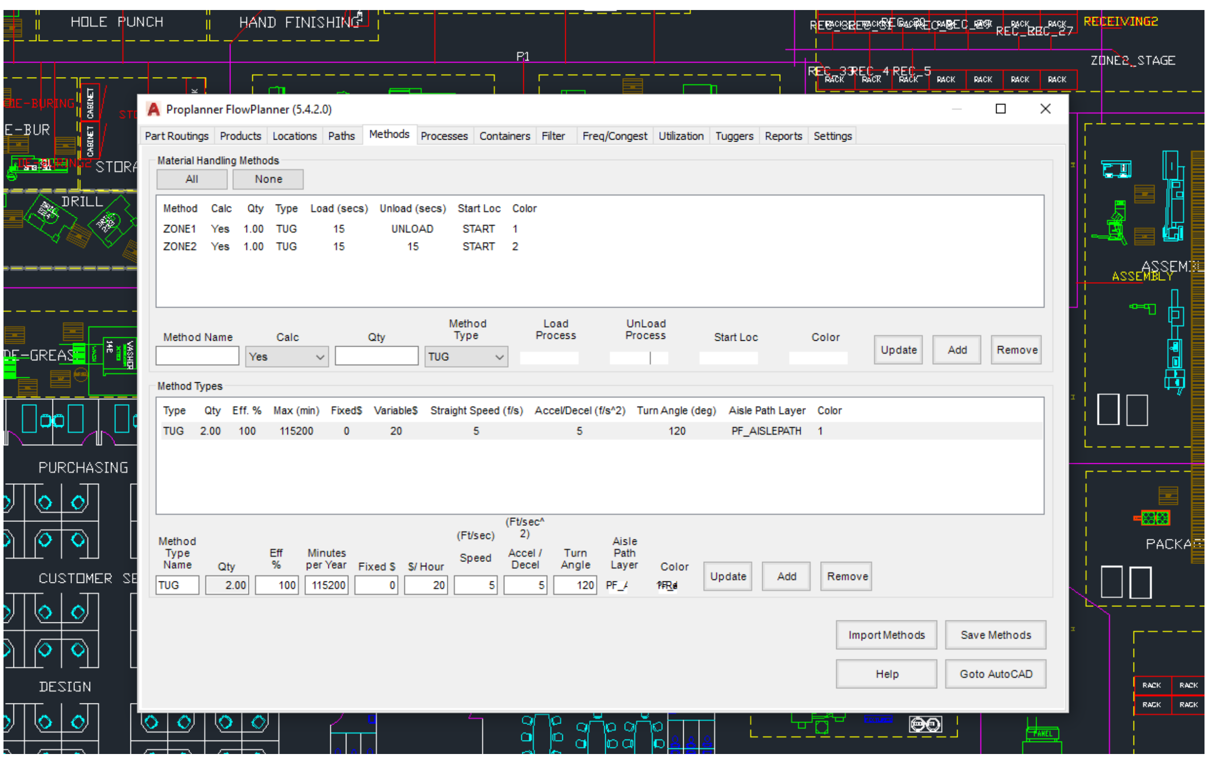


Figure 13: Flow Planner Methods tab of the sample tugger analysis

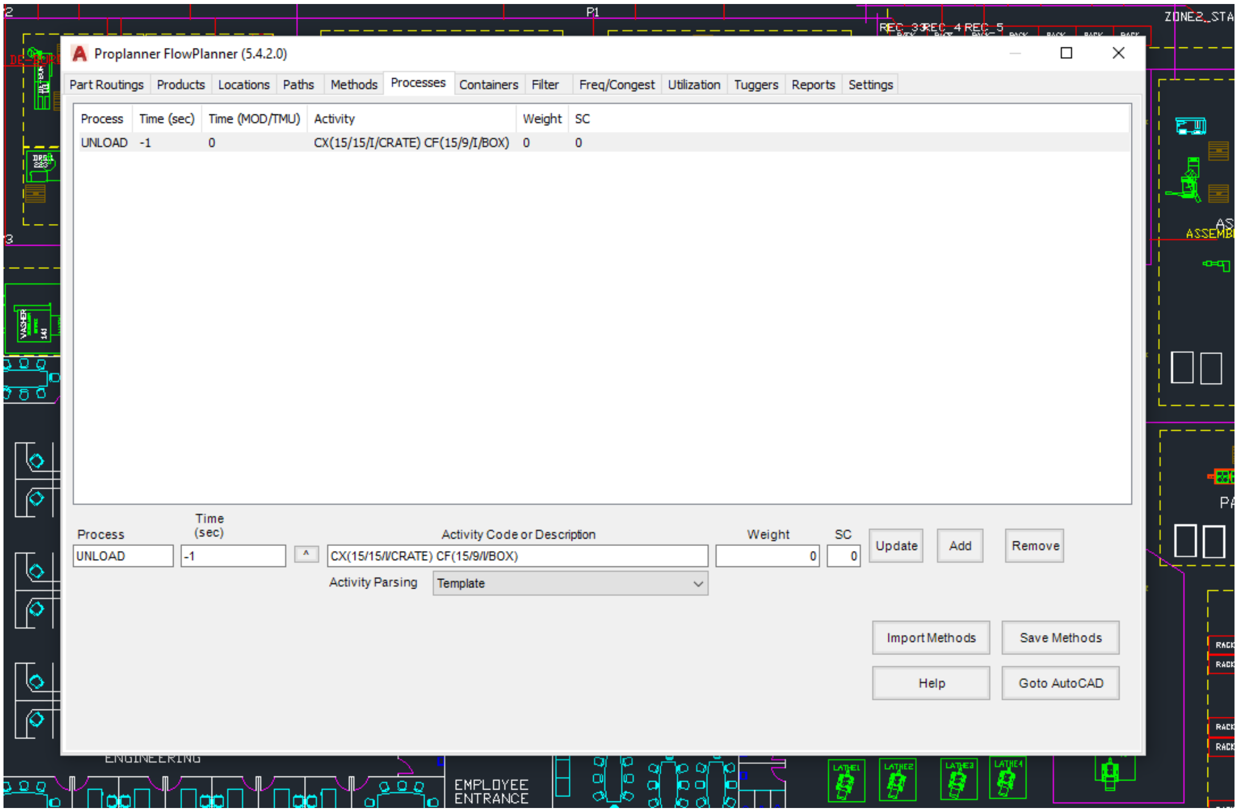


Figure 14: Flow Planner Processes tab of the sample tugger analysis

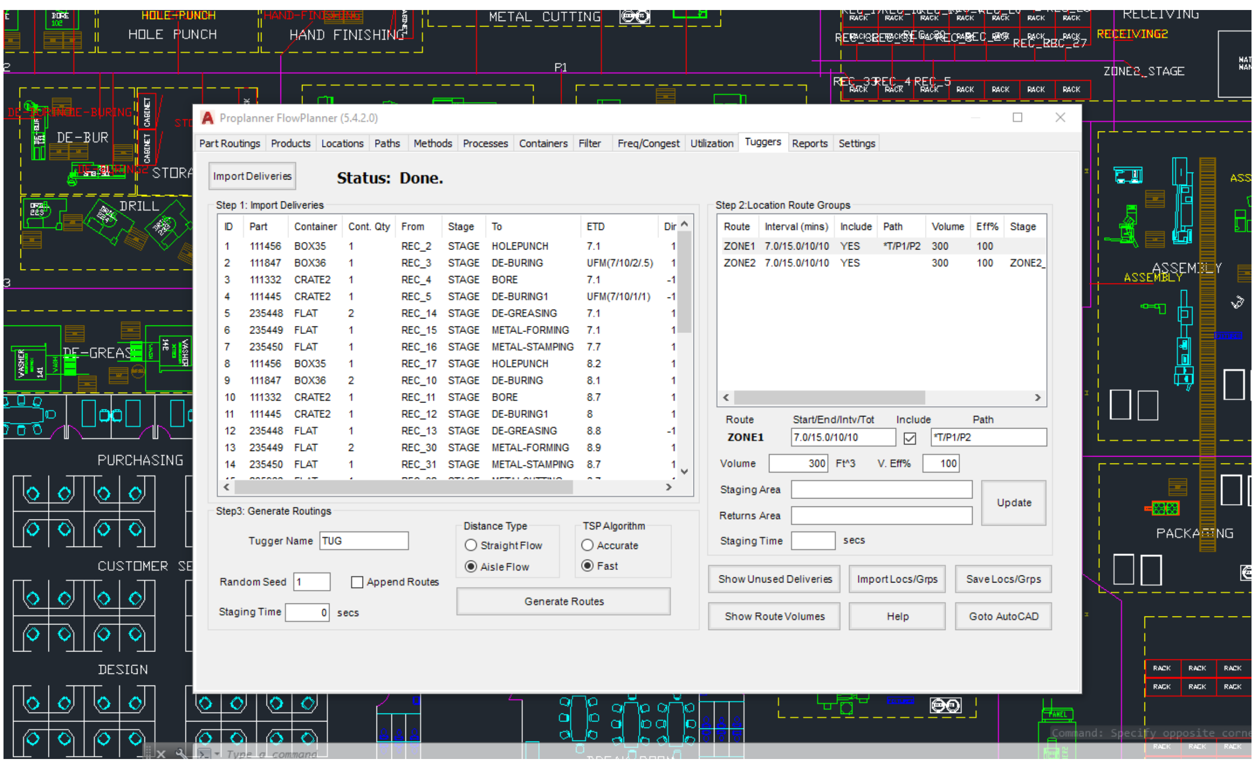


Figure 15: Flow Planner Tuggers tab of the sample tugger analysis

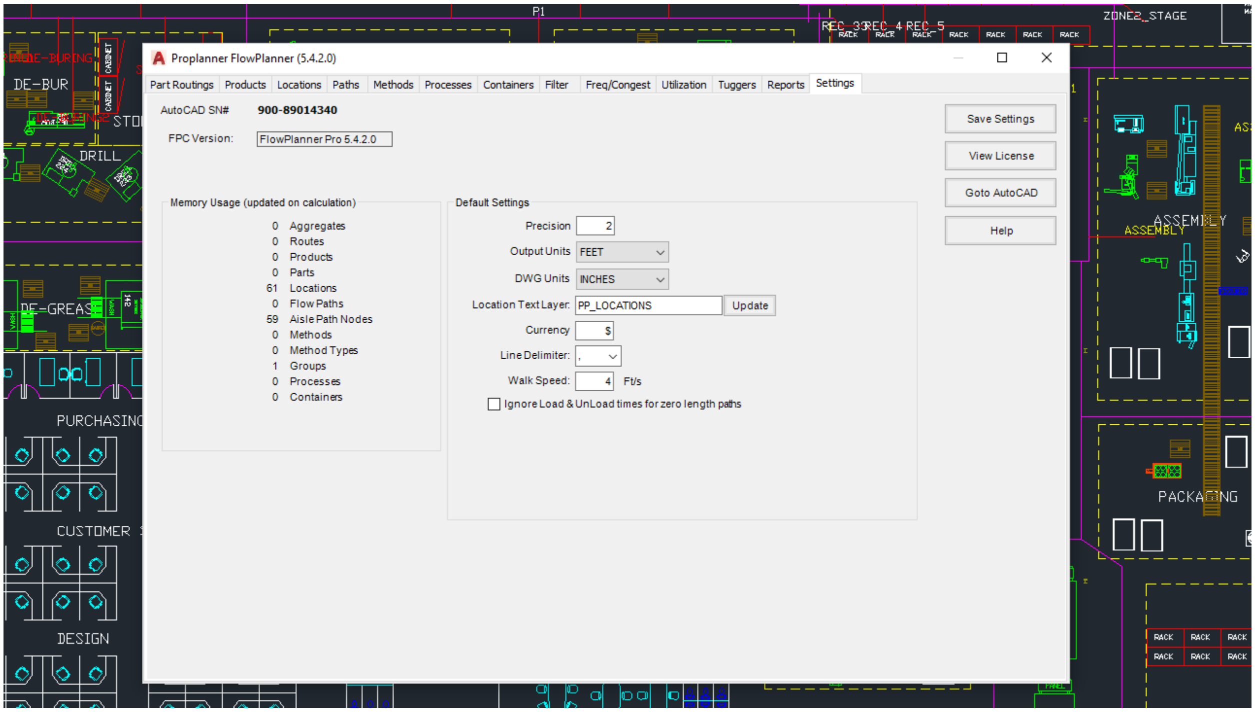


Figure 16: Flow Planner Settings tab of the sample tugger analysis

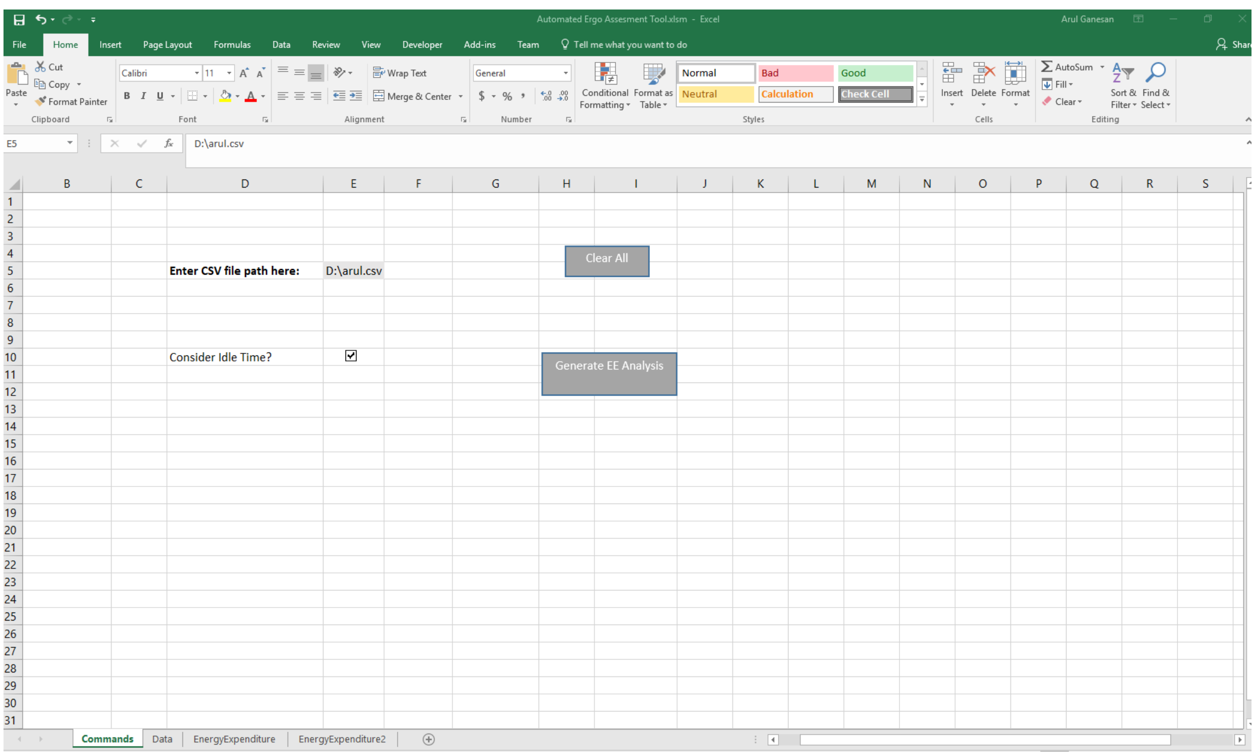


Figure 17: Sheet1 of the automated energy expenditure calculation program created

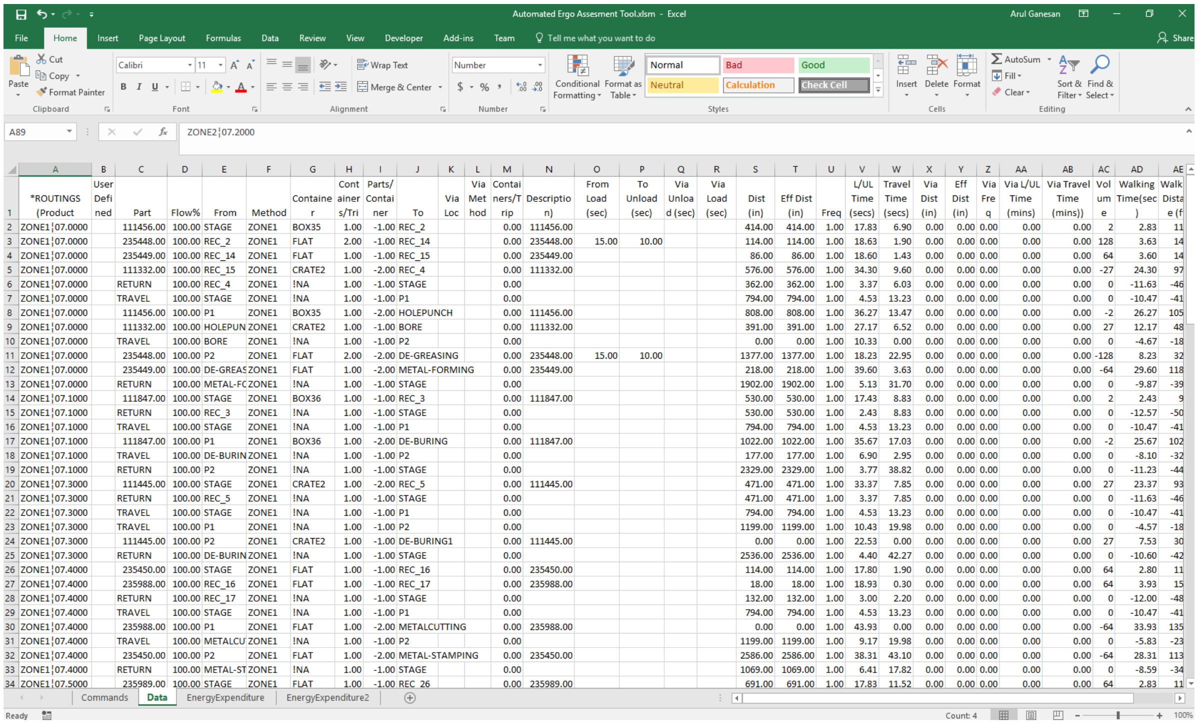


Figure 18: Sheet2 of the automated energy expenditure calculation program created

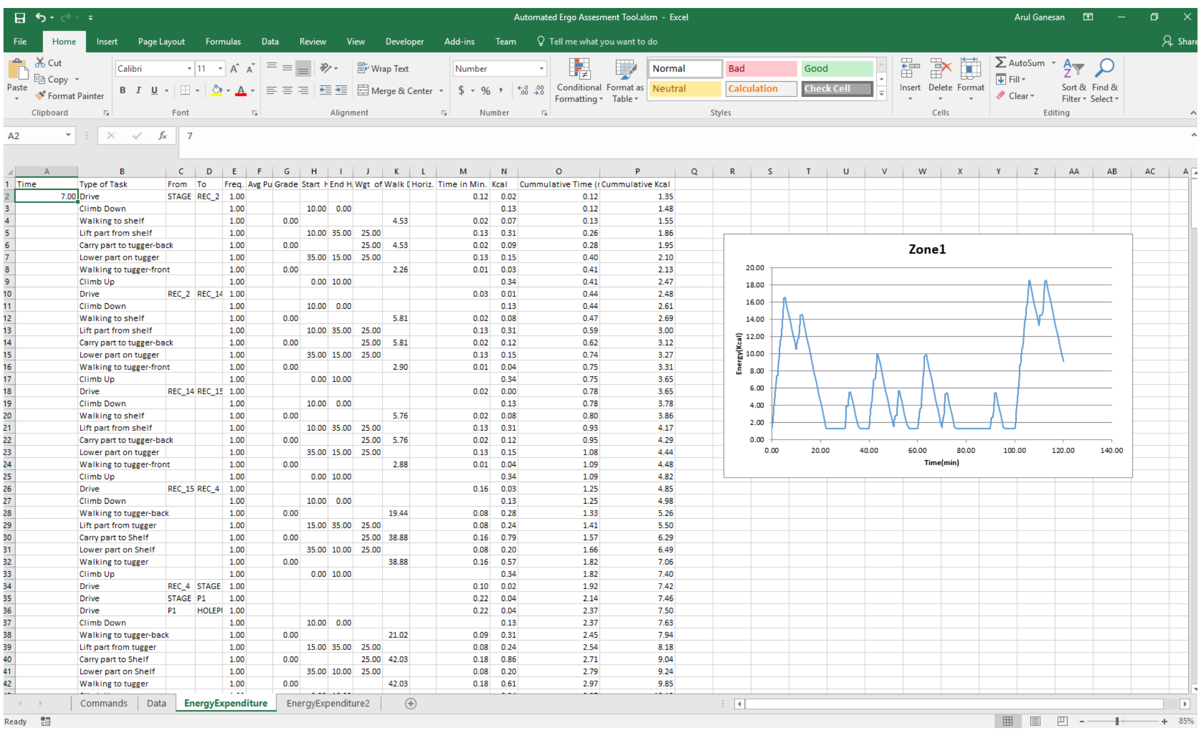


Figure 19: Sheet3 of the automated energy expenditure calculation program created