Optimizing Snow Plow Routes for the City of Bozeman

Matt Crocker, John Corbett, Brian Locke, Ty Show

Need for Snow Removal

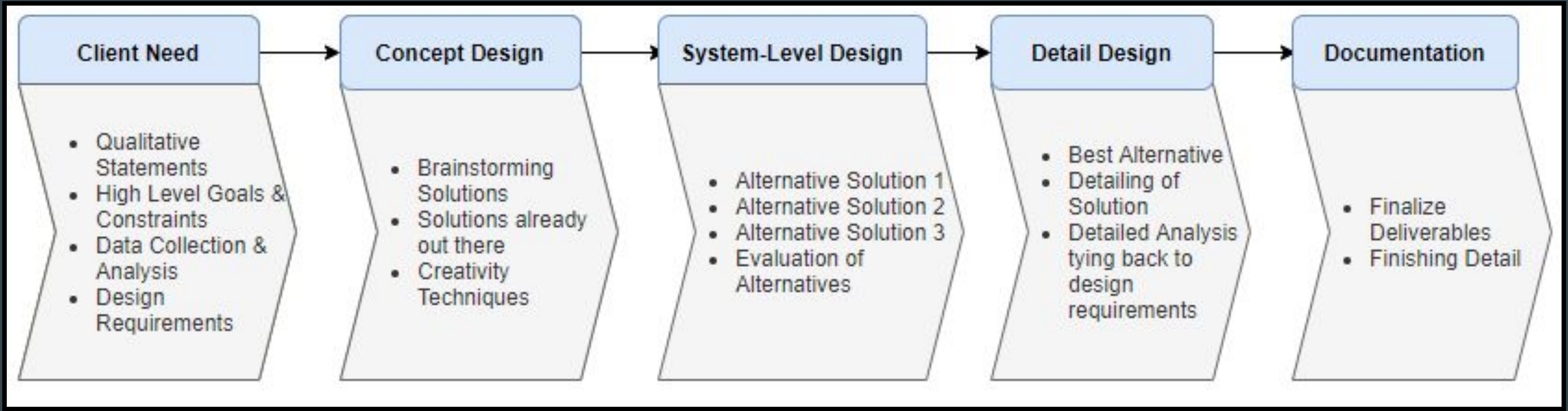
Economic Impact

- Commute times
- Deciding to stay home
- Not contributing to economy
- Increased lead time for deliveries

Safety

- Pedestrians' safety
- Driver's safety
- Emergency services
- Property damage

Engineering Design Process



Project Scope

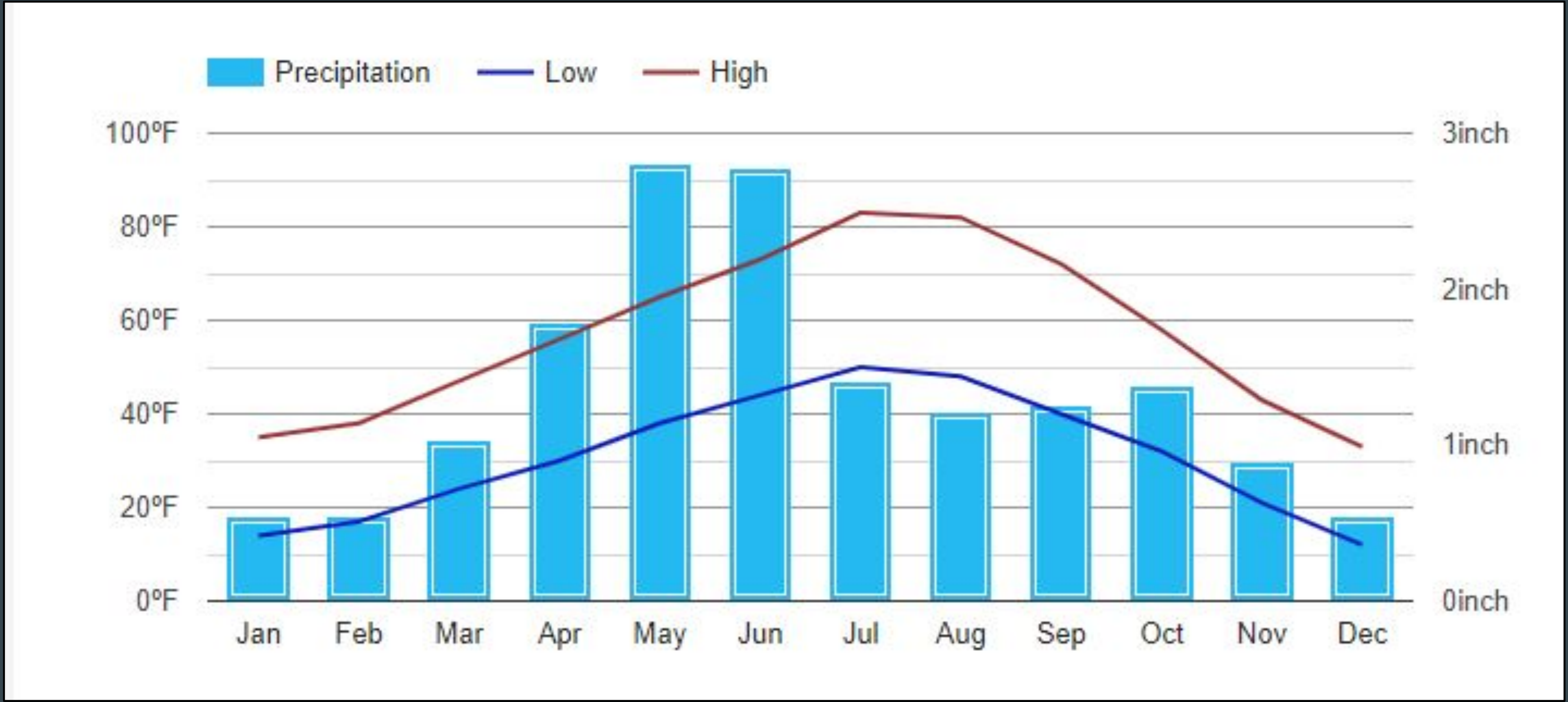
The client is interested in optimized routes for:

- Clearing all priority streets in 3-4 hours when a major snow event occurs.
- All proposed solutions should not add to the risk of accidents or increase employee turnover

Background

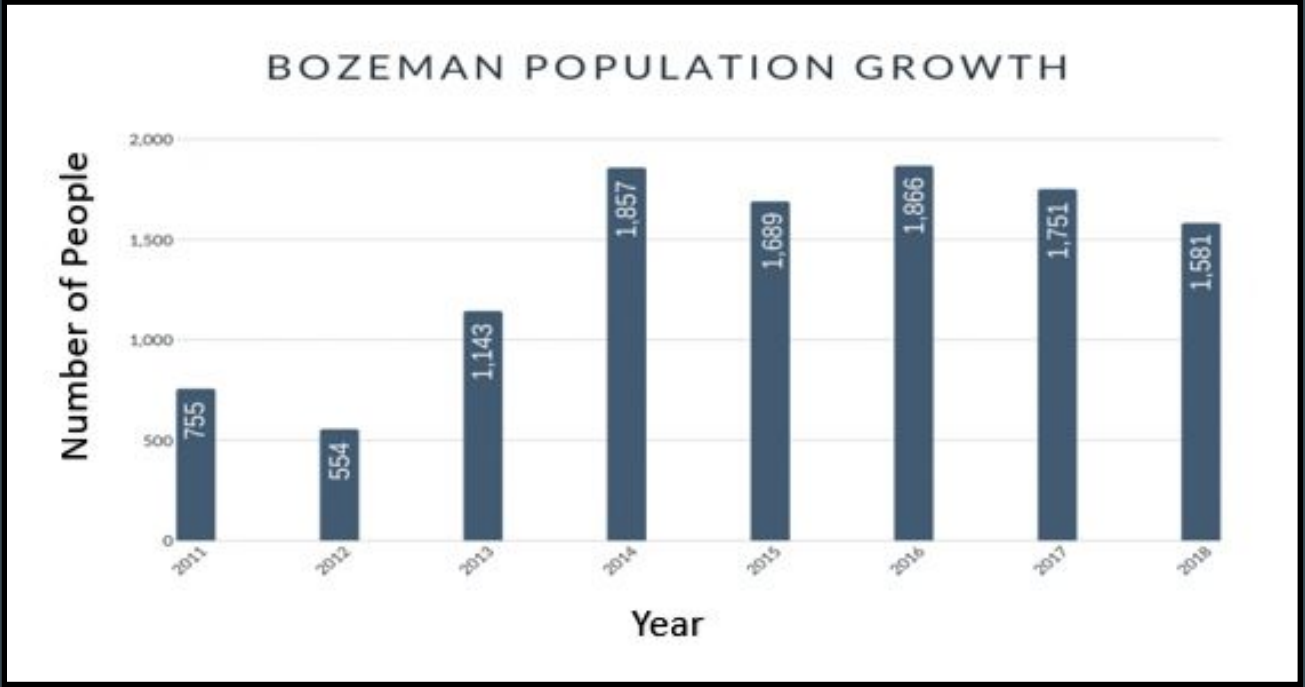
Client Need

City of Bozeman - Precipitation



Population Growth

Client Need



Project Objectives

1. Minimize the time required for plowing high priority streets
2. Improve method of route communication to plow operators

Metrics of Success

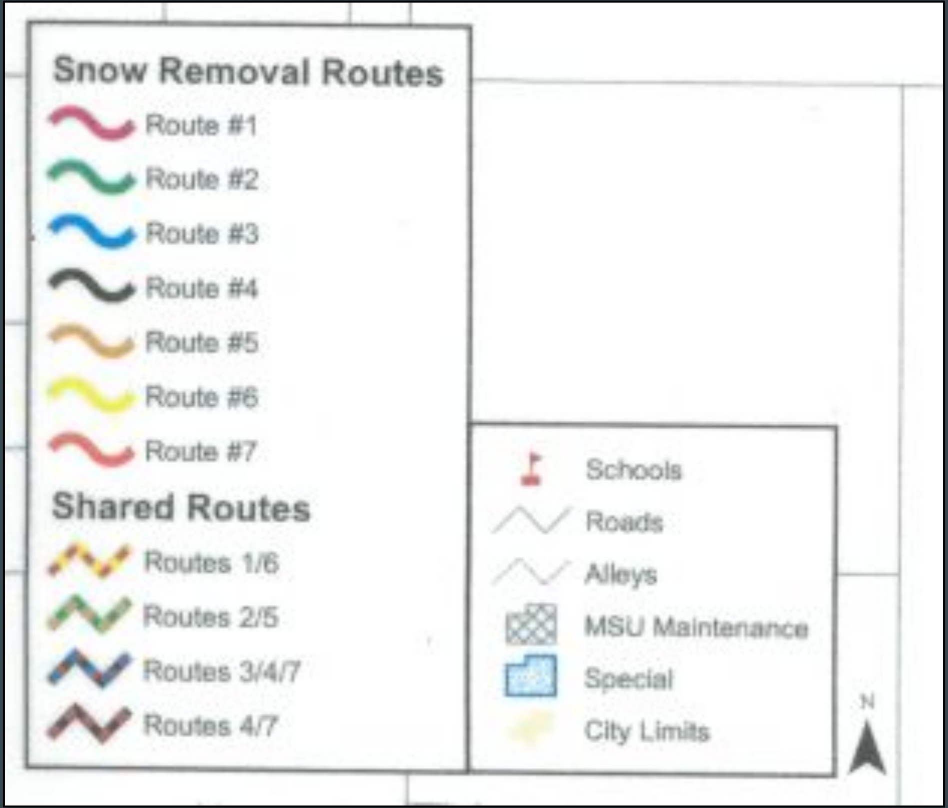
1. Plow time or projected plow time
2. Cost savings and increases
3. Usability of plow routes
4. Usability of route communication method

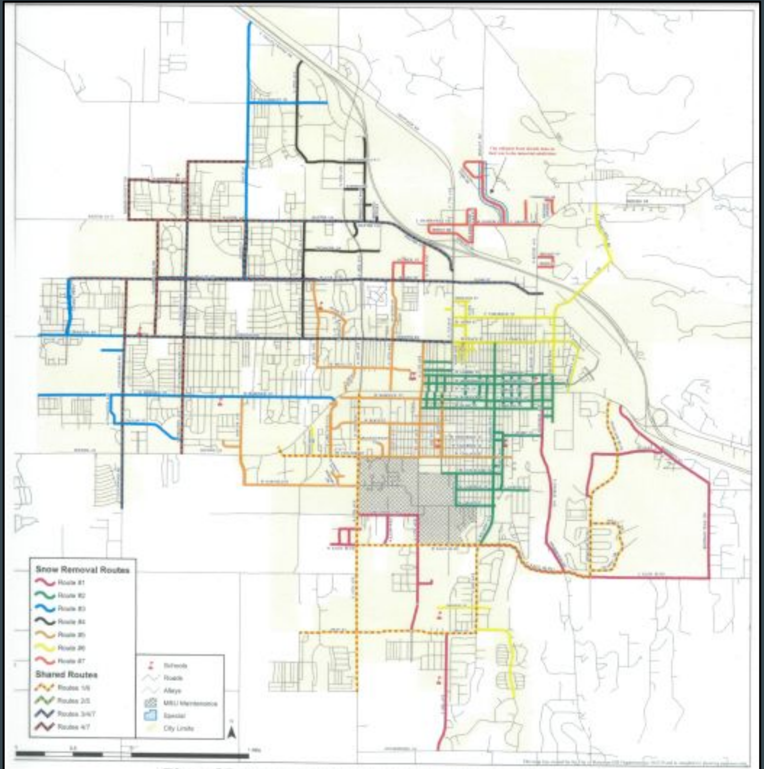
Project Constraints

- 8 plows available
- Software should be compatible with city systems
- Limit proposed spending

Current State

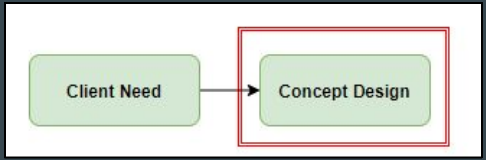
Client Need

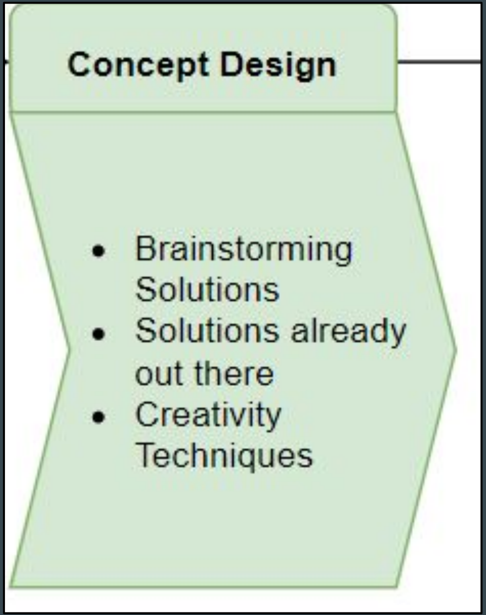


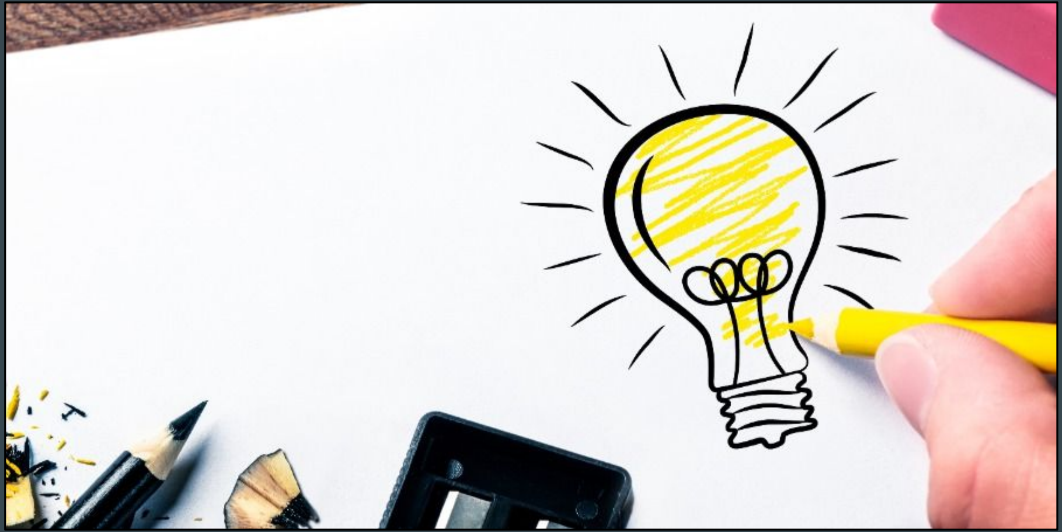


City of Bozeman Snow & Ice Control and Removal

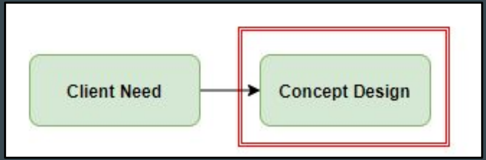
Concept Design







Brainstorm Ideas



Simulation

- Discrete event simulation

Linear Programming

- Mathematically determine optimal routes

Discussions with Faculty

Dr. David Claudio

Associate Professor: Mechanical & Industrial Engineering

Montana State University

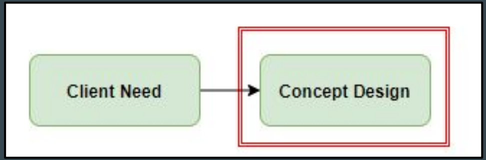
Dr. Sean Harris

Instructor:

Jake Jabs College of Business & Entrepreneurship

Montana State University

Linear Programming



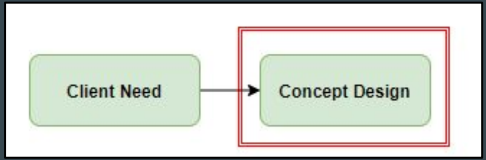
Optimizing systems

- Helps solve real world problems
- Applied linear algebra
- You can optimize systems that have large amounts of variables

Ex: UPS/Amazon/airlines

amazon

Literature Review

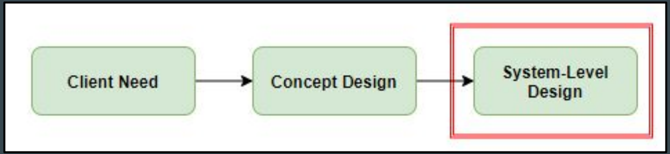


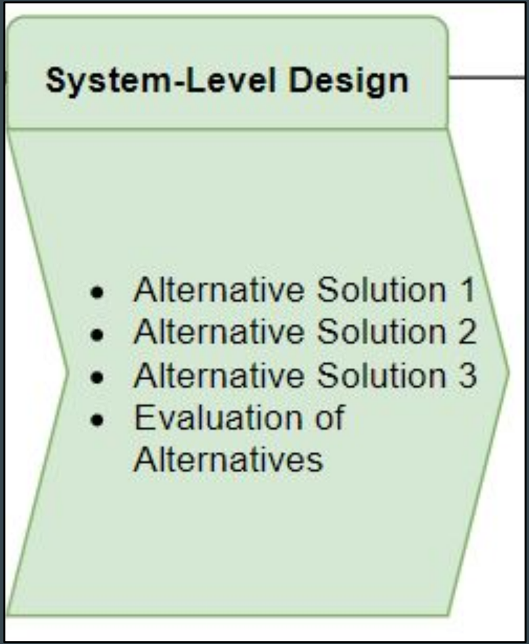
Highest priority to peer reviewed journal articles

Routing methods:

- Chinese Postman Problem Variants
- Traveling Salesman Model
- Synchronized Arc Routing
- Genetic Approach to Real Time Vehicle Dispatch

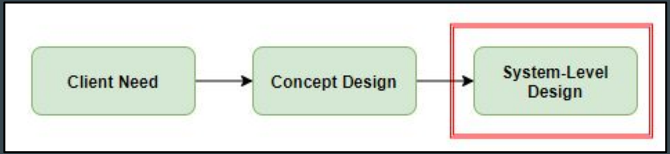
System-Level Design





Evaluation & Selection

Design Alternatives

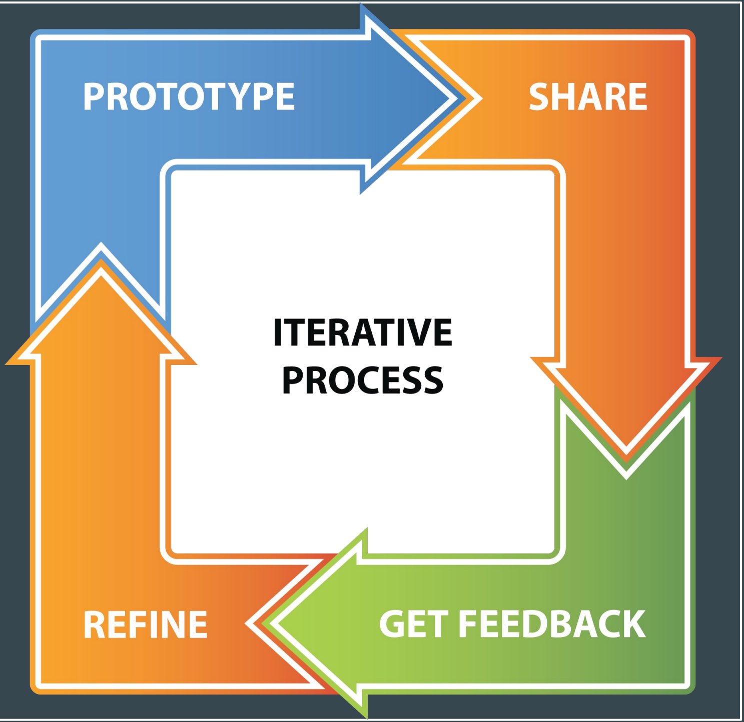


Design Alternative	Main Advantage
Windy Postman	Allows for change in path cost
Traveling Salesman	Relative simplicity
Synchronized Arc Routing	Allows for multiple plows traveling the same path simultaneously

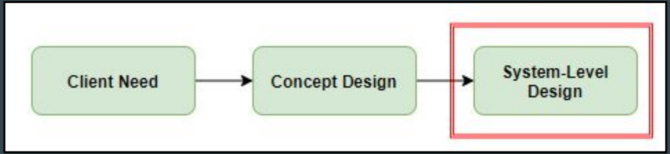
Design Requirements

From Established Objectives

1. Can model multiple entities
2. Only requires inputs available from data
3. Compatible software
4. Applicability to the situation
5. Allows for weighting in the objective function
6. Complexity of the model



Decision Matrix

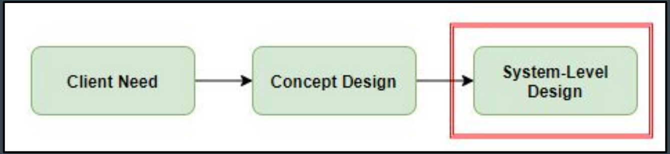


How well do the design alternatives fit the design requirements?

TITLE: Evaluation Matrix for Alternative Modeling Techniques

		Can model multiple entities	Only requires inputs that we can get from the data	Compatible Software	Applicability to the situation	Allows for weighing in the Objective Function	Complexity to model	TOTALS
WEIGHT		0.2	0.3	0.05	0.2	0.05	0.2	1
Alternative	Model	Requirement 1	Requirement 2	Requirement 3	Requirement 4	Requirement 5	Requirement 6	Requirement Total
1	Windy Postman Model	0.4	1.2	0.15	1	0.05	0.6	3.4
2	Traveling Salesman Model	1	1.5	0.15	0.8	0.25	1	4.7

Design Selection



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WEIGHT		0.2	0.3	0.05	0.2	0.05	0.2	1
Alternative	Model	Requirement 1	Requirement 2	Requirement 3	Requirement 4	Requirement 5	Requirement 6	Requirement Total
1	Windy Postman Model	0.2	0.9	0.15	0.6	0.05	0.6	2.5
3	Synchronized Arc Routing Model	1	0.3	0.15	1	0.25	0.2	2.9

TITLE: Evaluation Matrix for Alternative Modeling Techniques

		Can model multiple entities	Only requires inputs that we can get from the data	Compatible Software	Applicability to the situation	Allows for weighing in the Objective Function	Complexity to model	TOTALS
WEIGHT		0.2	0.3	0.05	0.2	0.05	0.2	1
Alternative	Model	Requirement 1	Requirement 2	Requirement 3	Requirement 4	Requirement 5	Requirement 6	Requirement Total
2	Traveling Salesman Model	1	1.5	0.15	0.8	0.25	1	4.7
3	Synchronized Arc Routing Model	1	0.3	0.15	1	0.15	0.2	2.8

TITLE: Evaluation Matrix for Alternative Modeling Techniques

		Can model multiple entities	Only requires inputs that we can get from the data	Compatible Software	Applicability to the situation	Allows for weighing in the Objective Function	Complexity to model	TOTALS
WEIGHT		0.2	0.3	0.05	0.2	0.05	0.2	1
Alternative	Model	Requirement 1	Requirement 2	Requirement 3	Requirement 4	Requirement 5	Requirement 6	Requirement Total
1	Windy Postman Model	0.3	1.05	0.15	0.8	0.05	0.6	2.95
2	Traveling Salesman Model	1	1.5	0.15	0.8	0.25	1	4.7
3	Synchronized Arc Routing Model	1	0.3	0.15	1	0.2	0.2	2.85

Design Selection

TITLE: Evaluation Matrix for Alternative Modeling Techniques		Can model multiple entities	Only requires inputs that we can get from the data	Compatible Software	Applicability to the situation	Allows for weighting in the Objective Function	Complexity to model	TOTALS
WEIGHT		0.2	0.3	0.05	0.2	0.05	0.2	1
Alternative	**Model**	Requirement 1	Requirement 2	Requirement 3	Requirement 4	Requirement 5	Requirement 6	**Requirement Total**
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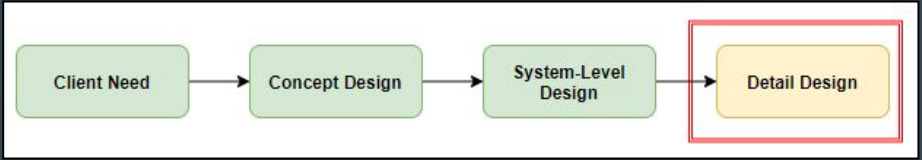
3	Synchronized Arc Routing Model	1	0.3	0.15	1	0.2	0.2	**2.85**

Simplest Case



$$t_{ij} = \begin{cases} 0 & \textit{if the plow does not travel from node i to node j} \\ 1 & \textit{if the plow does travel from node i to node j} \end{cases}$$

$$c_{ij} = \textit{ cost to travel from node i to node j}$$

Decision variable

Cost matrix

$$Min\ z = \sum_{i} \sum_{j} t_{ij} * c_{ij}$$

Time

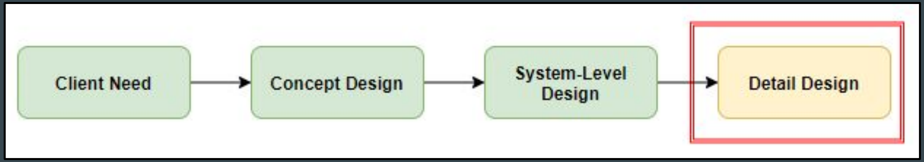
In = Out

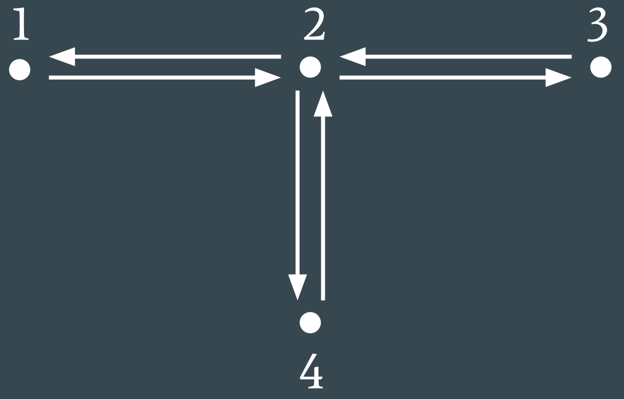
$$0 = \sum_{i} \sum_{j} t_{ij}\ \textit{representing arcs in} - t_{ij}\ \textit{representing arcs out} \quad \forall\ \textit{nodes}$$

Sets which streets require plowing

$$1 = t_{ij} \quad \forall\ \textit{arcs that require plowing}$$

Adding Turn Penalties



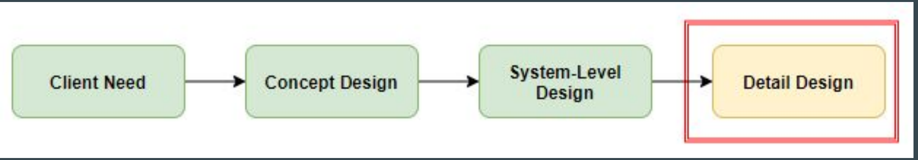


If $t_{12} = 1$ and $t_{24} = 1$, or $t_{32} = 1$ and $t_{24} = 1$, then the plow was traveling on road 123 and turned onto road 24.

If $t_{42} = 1$ and $t_{21} = 1$, or $t_{42} = 1$ and $t_{23} = 1$, then the plow was traveling on road 24 and turned onto road 123.

$$\ldots + c_t * (t_{12} * t_{24} + t_{32} * t_{24} + t_{42} * t_{21} + t_{42} * t_{23})$$

Adding Turn Penalties



$$t_{ijkl} = \begin{cases} 0 & if\ plow\ l\ does\ not\ travel\ from\ node\ i\ to\ node\ j \\ 1 & if\ plow\ l\ does\ travel\ from\ node\ i\ to\ node\ j \end{cases}$$

$$c_{ij} = cost\ to\ travel\ from\ node\ i\ to\ node\ j$$

$$c_t = cost\ to\ turn$$

Decision variable

Cost matrix

Turn penalty

Time

$$Min\ z = \left(\sum_i \sum_j \sum_k \sum_l t_{ijkl} * c_{ij} \right) + c_t * (turn\ penalty\ terms)$$

In = Out

$$0 = \sum_i \sum_j \sum_k t_{ijkl}\ representing\ arcs\ in - t_{ijkl}\ representing\ arcs\ out \quad \forall\ nodes \quad \forall\ l$$

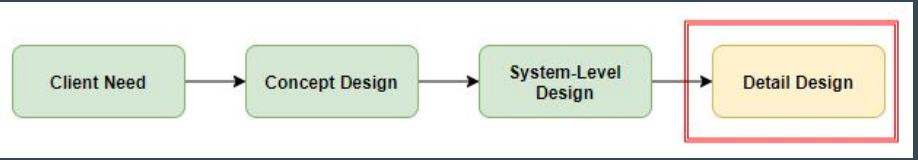
$$\#\ of\ lanes\ that\ require\ plowing \leq \sum_k \sum_l t_{ijkl} \quad \forall\ arcs$$

Sets which streets require plowing

Prevents routes of excessive length

$$\#\ of\ hours\ allowable\ per\ driver \geq \sum_i \sum_j \sum_k t_{ijkl} * c_{ij} \quad \forall\ l$$

Final Model Formulation



$$t_{ijkl} = \begin{cases} 0 & if\ plow\ l\ does\ not\ travel\ from\ node\ i\ to\ node\ j \\ 1 & if\ plow\ l\ does\ travel\ from\ node\ i\ to\ node\ j \end{cases}$$

$$c_{ij} = cost\ to\ travel\ from\ node\ i\ to\ node\ j$$

$$c_t = cost\ to\ turn$$

$$Min\ z = \left(\sum_i \sum_j \sum_k \sum_l t_{ijkl} * c_{ij}\right) + c_t * (turn\ penalty\ terms)$$

$$Min\ z = \left(\sum_i \sum_j \sum_k \sum_l t_{ijkl} * c_{ij}\right) + c_t * (turn\ penalty\ terms)$$

$$0 = \sum_i \sum_j \sum_g \sum_k t_{ijkl} - t_{jgkl} \quad \forall\ nodes \quad \forall\ l$$

$$0 \geq \sum_i \sum_j t_{ijkl} - \sum_j \sum_g t_{jgkl} \quad \forall\ j \quad \forall\ k \quad \forall\ l$$

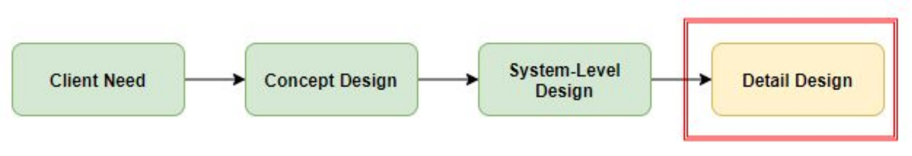
$$\#\ of\ required\ passes\ by\ plows \leq \sum_k \sum_l t_{ijkl} \quad \forall\ arcs$$

$$\#\ of\ required\ passes\ by\ graders \leq \sum_k \sum_l t_{ijk1} + t_{ijk2} \quad \forall\ arcs$$

$$\#\ of\ hours\ allowable\ per\ driver \geq \sum_i \sum_j \sum_k t_{ijkl} * c_{ij} \quad \forall\ l$$

$$1 = \sum_j t_{270j1l} \quad \forall\ l$$

Running the Model



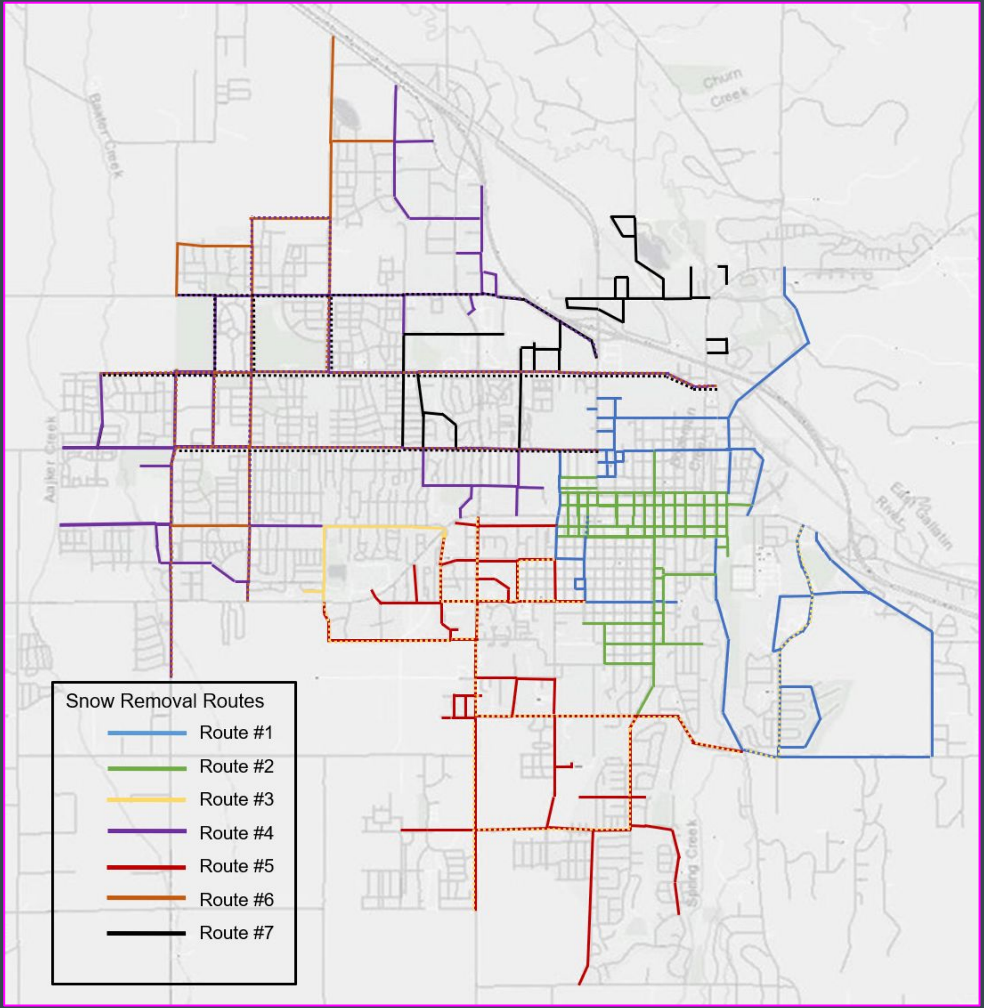
- For networks of this size, the number of variables will cause problems
- Compromises had to be made to run the model in under 8 hours with 3 Gb of RAM
- The routes obtained as output are not optimal solutions, but are good solutions

Recent Jobs (Last 45 days, Max 200 jobs)

Job #	Category	Solver	Input	Submitted	Elapsed	Status	Results
8137103	milp	CPLEX	AMPL	2020-05-02 05:41:34	7:30:16	Done	
8137102	milp	CPLEX	AMPL	2020-05-02 05:41:33	7:30:17	Done	
8137101	milp	CPLEX	AMPL	2020-05-02 05:41:31	2:20:17	Done	
8137100	milp	CPLEX	AMPL	2020-05-02 05:41:31	1:00:50	Done	
8137065	milp	CPLEX	AMPL	2020-05-02 04:22:39	0:45:07	Done	
8137063	milp	CPLEX	AMPL	2020-05-02 04:19:23	0:00:05	Done	
8137062	milp	CPLEX	AMPL	2020-05-02 04:14:27	7:30:03	Done	
8137061	milp	CPLEX	AMPL	2020-05-02 04:14:26	0:00:02	Done	
8137057	milp	CPLEX	AMPL	2020-05-02 04:09:31	7:30:03	Done	
8137056	milp	CPLEX	AMPL	2020-05-02 04:09:29	0:00:02	Done	
8137055	milp	CPLEX	AMPL	2020-05-02 04:05:21	7:30:03	Done	
8137054	milp	CPLEX	AMPL	2020-05-02 04:05:19	0:00:02	Done	
8137050	milp	CPLEX	AMPL	2020-05-02 03:56:13	7:30:07	Done	
8137049	milp	CPLEX	AMPL	2020-05-02 03:56:11	0:00:07	Done	
8137048	milp	CPLEX	AMPL	2020-05-02 03:56:10	7:30:09	Done	
8137047	milp	CPLEX	AMPL	2020-05-02 03:56:09	0:00:09	Done	
8137001	milp	CPLEX	AMPL	2020-05-02 02:35:05	7:30:13	Done	
8137000	milp	CPLEX	AMPL	2020-05-02 02:35:03	7:30:16	Done	
8136990	milp	CPLEX	AMPL	2020-05-02 02:32:26	7:30:12	Done	
8136989	milp	CPLEX	AMPL	2020-05-02 02:32:25	7:30:12	Done	
8136646	milp	CPLEX	AMPL	2020-05-01 20:30:14	7:30:24	Done	
8136645	milp	CPLEX	AMPL	2020-05-01 20:30:13	7:30:28	Done	
8136644	milp	CPLEX	AMPL	2020-05-01 20:30:11	7:30:26	Done	
8136643	milp	CPLEX	AMPL	2020-05-01 20:30:10	7:30:08	Done	
8136507	milp	CPLEX	AMPL	2020-05-01 17:37:48	0:06:57	Done	
8136506	milp	CPLEX	AMPL	2020-05-01 17:37:46	7:30:11	Done	
8136457	milp	CPLEX	AMPL	2020-05-01 17:13:14	0:33:31	Done	
8136456	milp	CPLEX	AMPL	2020-05-01 17:13:12	7:30:08	Done	
8136425	milp	CPLEX	AMPL	2020-05-01 17:02:54	1:18:00	Done	
8136424	milp	CPLEX	AMPL	2020-05-01 17:02:53	0:06:58	Done	
8135101	milp	CPLEX	AMPL	2020-05-01 11:05:38	7:30:22	Done	
8135100	milp	CPLEX	AMPL	2020-05-01 11:05:36	7:30:22	Done	
8135099	milp	CPLEX	AMPL	2020-05-01 11:05:35	7:30:22	Done	
8135098	milp	CPLEX	AMPL	2020-05-01 11:05:33	7:30:13	Done	
8135078	milp	CPLEX	AMPL	2020-05-01 10:59:56	0:00:10	Done	
8135077	milp	CPLEX	AMPL	2020-05-01 10:59:54	0:00:12	Done	
8135076	milp	CPLEX	AMPL	2020-05-01 10:59:51	0:00:13	Done	
8135075	milp	CPLEX	AMPL	2020-05-01 10:59:50	0:00:13	Done	

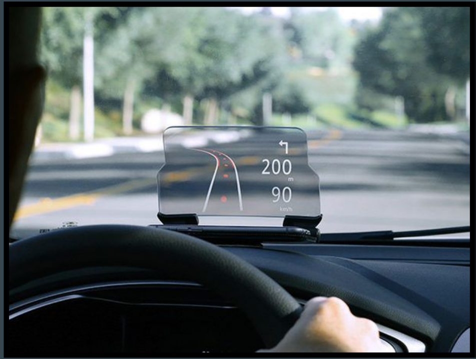
Final Optimized Routes

Assuming the longest current route takes 5 hours, the team provided routes that improved on the current routes by approximately 18 minutes or a <u>6% improvement.</u>



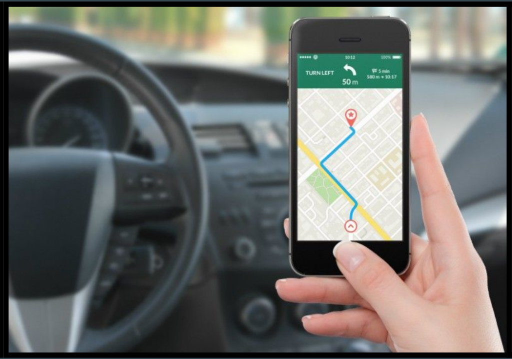
Route Communication Methods

Heads Up Displays

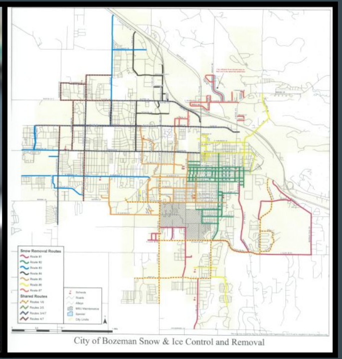


GPS units w/ Audio

Phone Navigation



Paper Maps



Evaluation of Methods

Route Communication Method Goals:

- Increase the usability of snow plow route communication
- Create countermeasures for line of sight distractions due to current map method
- Decrease distractions due to route communication
- Increase amount of standard operating procedures (SOP's) for method

Route Communication Method Constraints:

- The countermeasures should be relatively easy to install
- The countermeasures should be low cost
- The new system should stay in line with the overall project goals
- The new system should not make the job harder or less safe

Stakeholder Analysis

Priority Weighting of Design Requirements

Priority Weighting of Design Requirements

TITLE: Evaluation Matrix for Alternative Communication Methods — 1 & 2 Comparison

Alternative	Model	Requirement 1 (Limited Complexity of Technique)	Requirement 2 (Easy Implementation)	Requirement 3 (Programmable, or ability to input different routes)	Requirement 4 (Reduce Chance of accidents)	Requirement 5 (Limited line of sight movement)	Requirement Total (TOTALS)
	WEIGHT						0
1	Heads Up Displays	3	2	3	4	4	16
2	Dash based GPS with Audio Directions	5	3	3	5	5	21

0	Completely Not Satisfied
1	Mostly Not Satisfied,
2	Somewhat not Satisfied
3	Somewhat Satisfied
4	Mostly Satisfied
5	Completely Satisfied

TITLE: Evaluation Matrix for Alternative Communication Methods — 2 & 3 Comparison

Alternative	Model	Requirement 1 (Limited Complexity of Technique)	Requirement 2 (Easy Implementation)	Requirement 3 (Programmable, or ability to input different routes)	Requirement 4 (Reduce Chance of accidents)	Requirement 5 (Limited line of sight movement)	Requirement Total (TOTALS)
	WEIGHT						0
2	Dash Based GPS with Audio Directions	5	3	4	5	5	22
3	Phone Based GPS with Audio Direction	4	5	4	3	5	21

0	Completely Not Satisfied
1	Mostly Not Satisfied,
2	Somewhat not Satisfied
3	Somewhat Satisfied
4	Mostly Satisfied
5	Completely Satisfied

TITLE: Evaluation Matrix for Alternative Communication Methods — 1 & 3 Comparison

Alternative	Model	Requirement 1 (Limited Complexity of Technique)	Requirement 2 (Easy Implementation)	Requirement 3 (Programmable, or ability to input different routes)	Requirement 4 (Reduce Chance of accidents)	Requirement 5 (Limited line of sight movement)	Requirement Total (TOTALS)
	WEIGHT						0
1	Heads Up Displays	3	2	3	4	5	17
3	Phone based GPS with audio directions	5	3	3	5	4	20

0	Completely Not Satisfied
1	Mostly Not Satisfied,
2	Somewhat not Satisfied
3	Somewhat Satisfied
4	Mostly Satisfied
5	Completely Satisfied

TITLE: Evaluation Matrix for Alternative Communication Methods — 2 & 4 Comparison

Alternative	Model	Requirement 1 (Limited Complexity of Technique)	Requirement 2 (Easy Implementation)	Requirement 3 (Programmable, or ability to input different routes)	Requirement 4 (Reduce Chance of accidents)	Requirement 5 (Limited line of sight movement)	Requirement Total (TOTALS)
	WEIGHT						0
2	Dash based GPS with Audio Directions	4	4	4	5	5	22
4	Original Paper Maps	5	5	0	0	1	11

0	Completely Not Satisfied
1	Mostly Not Satisfied,
2	Somewhat not Satisfied
3	Somewhat Satisfied
4	Mostly Satisfied
5	Completely Satisfied

TITLE: Evaluation Matrix for Alternative Communication Methods — 1 & 4 Comparison

Alternative	Model	Requirement 1 (Limited Complexity of Technique)	Requirement 2 (Easy Implementation)	Requirement 3 (Programmable, or ability to input different routes)	Requirement 4 (Reduce Chance of accidents)	Requirement 5 (Limited line of sight movement)	Requirement Total (TOTALS)
	WEIGHT						0
1	Heads Up Displays	3	4	3	4	5	19
4	Original Paper Maps	5	5	0	0	1	11

0	Completely Not Satisfied
1	Mostly Not Satisfied,
2	Somewhat not Satisfied
3	Somewhat Satisfied
4	Mostly Satisfied
5	Completely Satisfied

TITLE: Evaluation Matrix for Alternative Communication Methods — 3 & 4 Comparison

Alternative	Model	Requirement 1 (Limited Complexity of Technique)	Requirement 2 (Easy Implementation)	Requirement 3 (Programmable, or ability to input different routes)	Requirement 4 (Reduce Chance of accidents)	Requirement 5 (Limited line of sight movement)	Requirement Total (TOTALS)
	WEIGHT						0
3	Phone based GPS with audio directions	5	4	4	3	2	18
4	Original Paper Maps	5	5	0	0	1	11

0	Completely Not Satisfied
1	Mostly Not Satisfied,
2	Somewhat not Satisfied
3	Somewhat Satisfied
4	Mostly Satisfied
5	Completely Satisfied

Recommendations

GPS with Audio Directions

Cost around $99.99 brand new

Refurbished units are priced in the $60 to $80 range.

TITLE: Summary Graph	Evaluation Matrix for Alternative Communication Methods	Limited Complexity of Technique	Easy Implementation	Programmable, or ability to input different routes	Reduce Chance of accidents	Limited line of sight movement	TOTALS
	WEIGHT	0.1	0.1	0.2	0.3	0.3	1
Alternative	Model	Requirement 1	Requirement 2	Requirement 3	Requirement 4	Requirement 5	Requirement Total
1	Heads Up Displays	0.3	0.3	0.6	1.2	1.4	3.8
2	Dash based GPS with Audio Directions	0.5	0.3	0.7	1.5	1.5	4.5
3	Phone based GPS with audio directions	0.5	0.4	0.7	1.1	1.1	3.8
4	Original Paper Maps	0.5	0.5	0.0	0.0	0.3	1.3

0	Completely Not Satisfied
1	Mostly Not Satisfied,
2	Somewhat not Satisfied
3	Somewhat Satisfied
4	Mostly Satisfied
5	Completely Satisfied

Route Communication Implementation Plan

Guide to transition from paper maps to GPS units with Audio directions

Plow Driver Training Session

Test Run of Routes

Activity		Start Date	Finish Date	Status/Comments
1	Purchase 8 GPS units			
2	Confirm software is up to date			
3	Load Optimized Snow Plow Routes onto devices			
4	Confirm all trucks have working 12 volt power outlet			
5	Fix any faulty 12 volt power outlets			
6	Schedule Driver GPS training session			
7	Plow Driver GPS training session			
8	Provide each truck with mounting solution			
9	Drivers mount/install GPS with suction cup to windshield			
10	Run power cable from GPS unit to 12 volt supply			
11	Confirm voice navigation is enabled			
12	Distribute Plow Route assignment to drivers			
13	Driver select assigned plow route in GPS unit			
14	Test run plow routes with GPS visual and audio communication			

Conclusion and Takeaways

- The route optimization provided routes that improved on the current routes by approximately 18 minutes or a 6% improvement.
- The use of GPS navigation units with turn-by-turn audio instructions can improve plow operator safety and reduce employee turnover

Q & A

References

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