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Development of Method and Tool for Optimizing the Earthwork with Ex-Situ Remediation of Polluted Soil

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I. Introduction

Whether it is with industrial remediation or with disaster remediation; remediation is always a challenge because of both the quite high technical requirements and implementation costs (Zithong, 2012). The development proposed in this article aims at sustaining some innovative ideas in the field of soil remediation with the implementation of precision remediation techniques in order to both reduce implementation costs and achieve remediation objectives more precisely. Our belief is that information technology could greatly improve the efficiency of the processes. In a previous study the author demonstrated the feasibility of precise remediation planning with the help of GIS technology and specifically designed geo-processing tools; and also demonstrated that precise planning spares earthwork (Lucas, 2015, Lucas 2016). Nevertheless one parameter was voluntarily omitted (the percentage of overlay between passages), another was chosen arbitrary[1] (the maximal line length). This study -which considers the field applications- targets these operational parameters and analyses how they affect efficiency.

Ex-situ remediation is exclusively targeted. Ex-situ remediation objectives are much different than those of classical excavation earthwork. Traditional earthwork considers volumes and their moves in a dig, fill and excavate approach. The approach is purely quantitative. Ex-situ remediation has to deal additionally with qualitative aspect: contaminated soil should be excavated whereas none contaminated should remain to the extent of possible untouched; also cross contamination should be avoided. In the case the remediation objective is 100% (so no pollution should be left on site) the planning and the field practices should avoid to leave pollution on site. As a consequence excavation practices should be adapted or even changed.

This study is organised in five parts. Part one sets the frame of the study with definitions, key concepts, objectives and hypothesis. The second part is a state of the art regarding optimization and efficiency in earthwork. The production line is analysed segment by segment and the latest developments with optimization are introduced. This part helps us to situate our developments inside the research landscape within the earthwork efficiency topic. Part three aims at testing and validating the hypothesis with the help of modelling. In part four a calibration method is proposed. Two parameters are controlled while experimenting with a model: the percentage of overlay (as an entry parameter) and maximal push length (measured). Then calibration curves are built. Finally a calculation tool is developed in the last part. It calculates optimized key parameters using the calibration results. Several set of parameters are used to test diverse scenarios with the scope to identify leverage parameters and refine the approach.

II. Important Concepts, Starting Points and Orientations

The problems dealt in this study are very specific and complex. We set some adapted terminology for their description. Additionally we made some decision regarding starting points and orientations. For the sake of clarity we would like to provide the reader with all the necessary information before to start with the development of research work.

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[1] The reason is these parameters were not relevant for the algorithm development, they make sense when considering the field approach and heavy equipment efficiency consideration.

a) Objectives

Efficiency is twofold in the frame of this study. First by order of importance is the technical efficiency, which means efficient achievement of the remediation objectives (the precise excavation of polluted soil). Secondly efficiency is also measured economically through the operation costs so as a higher efficiency would be less costly. Unless it is specified, the efficiency will refer to the technical efficiency. Our objectives follow the same hierarchy. First we consider the best technical achievements, and secondly will see how costs vary with the technical choices[2]. This choice is caused by the remediation process which at first is led by technical requirement: an objective for pollution removal. (ADEME 2006).

The remediation objectives are usually defined in a remediation plan. In particular the maximum amount of pollution that can remains after remediation work is accomplished. It can be 0% if all the pollution should be removed. It can be more if a certain amount of pollution can be left on site. In the frame of this study we decided to be able to cover diverse pollution removal objectives for several reasons. A 100% removal objective because we believe that technology should be used towards the best achievement[3]. The second reason is if dissimilarities happen between theory and practice, the practical achievement should still have high level. And lower removal objectives in order to offer a solution for less demanding remediation.

b) Machines combination

Table 1: Summarize the characteristics of the diverse equipment.

Machine type	Bull dozer	Wheel tractor/loader	Motor grader	Wheel tractor-scrapper
Overview				
Configuration	blade before tracks	blade before wheels	wheels before blade	wheels before blade
Collect efficiency	low (go/return and turn)	low (go/return and turn)	Medium (full line)	High (full line)
Robustness	Very high but can be stiff	High and flexible	limited to good condition	limited to good condition

Table 1 summary of the advantage and disadvantage of the three options.

Presently and after analysis of literature (CATERPILLAR, 2016; Nehaoua, 2013) we see three possible combination of equipment for performing the work, then we have made our own development regarding spacial coverage and work organisation in the field.

The first uses first dozers with parallel go, return and turn moves to make earth dump at the end of lines (fig.1a) and the cooperation with excavators to remove the earth dump and open the way for further work of the dozer (fig.1b). Because of the go and return moves it is not the less costly, nor the fastest approach, but it is applicable in any case as the robust equipment can perform work in any terrain conditions.

In the second motor grader equipment could replace the dozers. In that case the go, return and turn can be spared as the grading equipment can dump the contaminated soil in one passage in perpendicular direction compared to the moves of the former proposal (fig. 1c). In order to spare moves with the excavator the dump can be grouped every two passages. Then the excavator excavates the contaminated soil in the same way as with the first approach (fig. 1d).

[2] Our presumption is that technological support will help to increase work efficiency, avoid redo and expenses will dicrease proportionally.

[3] This does not mean that 100% will be acheived in the field. Field acheivevement can only be know with field tests.

The third use a tractor-scrapper and directly excavate the contaminated soil (fig. 1e). [4]

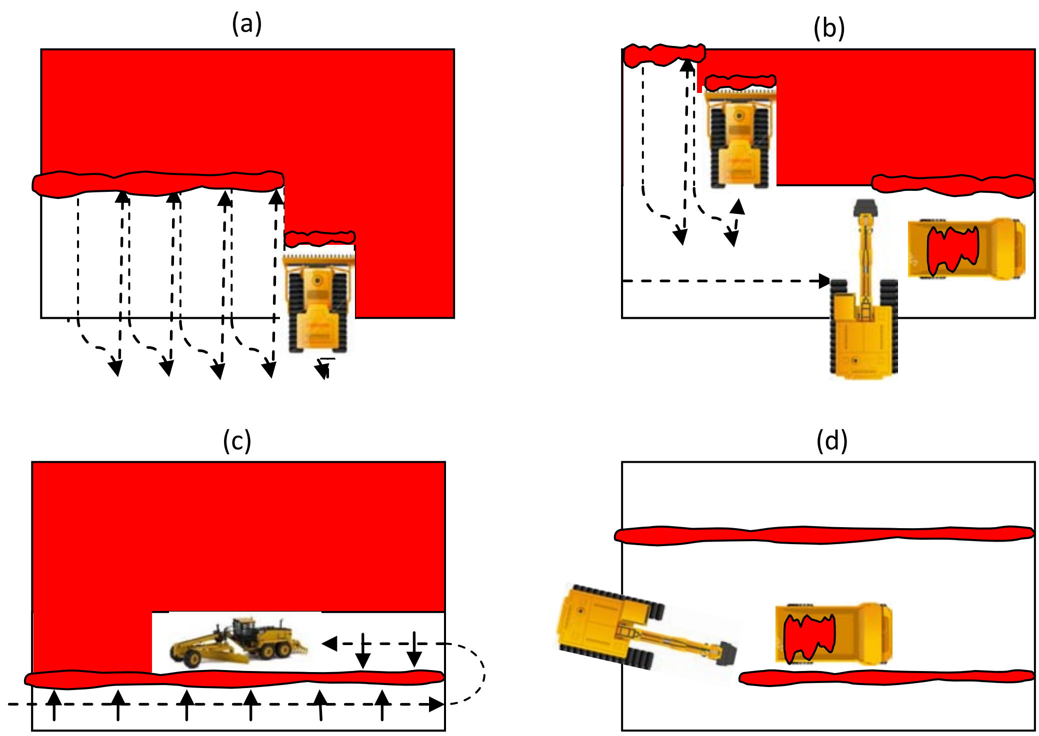

Fig.1: 3 possible cooperation approaches

The decision making for remediation method is a complex process where methods efficiencies, achievements and costs are compared (ADEME 2006, Colombano 2010). Depending on the situation (type of pollution, constraints) a method can be relevant in one case and not relevant in the other. This is the reason why the three options are considered and 3 different scenarios are proposed.

Among the criteria that can favour a method or another we can mention:

1. The consistency of the soil. If a soil has rock or heterogenic elements scrapper and grading equipment could be weak in these conditions (SETRA & LCPC, 2000).
2. Priority to time. In the case priority is given on time rather than on high level remediation objectives, it is profitable to use a fast approach (with a tractor-scrapper for example).
3. Accuracy objective. Some equipment (grading machine, scrapper) have front wheels before their grading equipment (fig. 2). Such configuration can bury pollution on sensitive soil. Moreover the front well can move pollution from contaminated area to clean (or cleaned) areas. If for example soil is sensitive to compression and remediation objectives are strict it would not be a good decision to use those equipments.

[4] the enforceability of different heavy equipment with the detailed analysis and the machine controll will be the subject of a specific publication

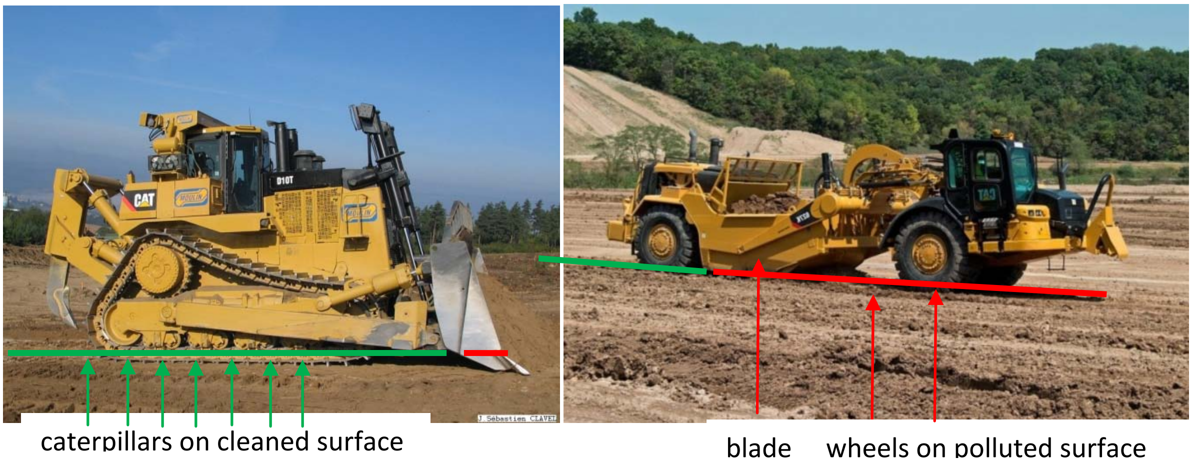

Fig.2: Comparison of configuration between a bulldozer and a tractor-scraper machinery

4. Sometime (in emergency situations for example) the technical solution depends mainly on the equipment immediately available.

c) *Details on the operations using dozer in the field*

While dozer performs work and material get accumulated in the blade some material is ejected on the sides of the blade. We called it "side dump" (fig. 3).

Figure 3: Side dump happening on the side of blade.

Side dump happens when the storage capacity of the equipment is reached after a certain distance was run. We call this distance "maximum line length" and note it l_{max} (fig. 4).

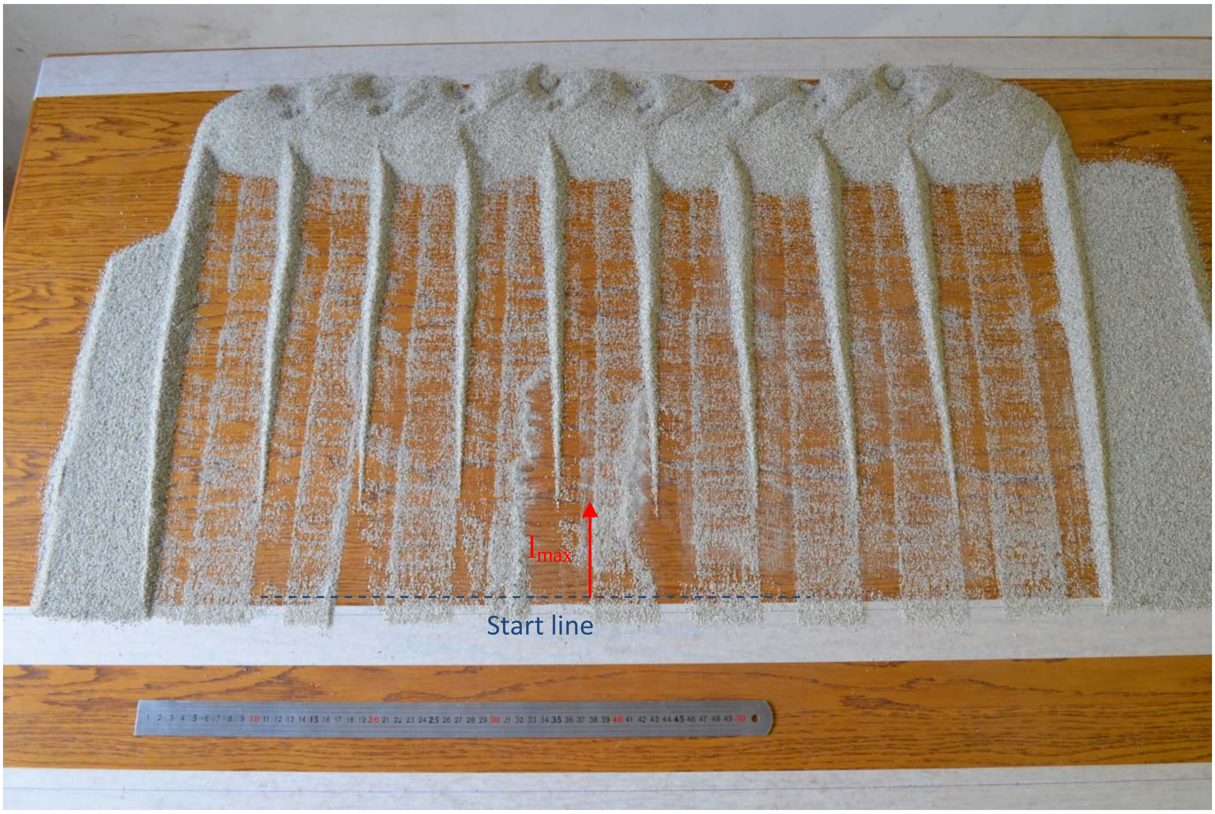

Figure 4: Maximum line length

The line length (noted l) is the length a dozer has gone from start point (time 0) to time t.

When side dump effect is not overcome polluted soil remains on site. To overcome side dump effect, the planning and the realisation have to integrate an overlay between the passages. Overlay is the percentage of lateral overlay between the two footprints of two blade passages (fig. 5). We express the overlay value as a percentage of the blade width.

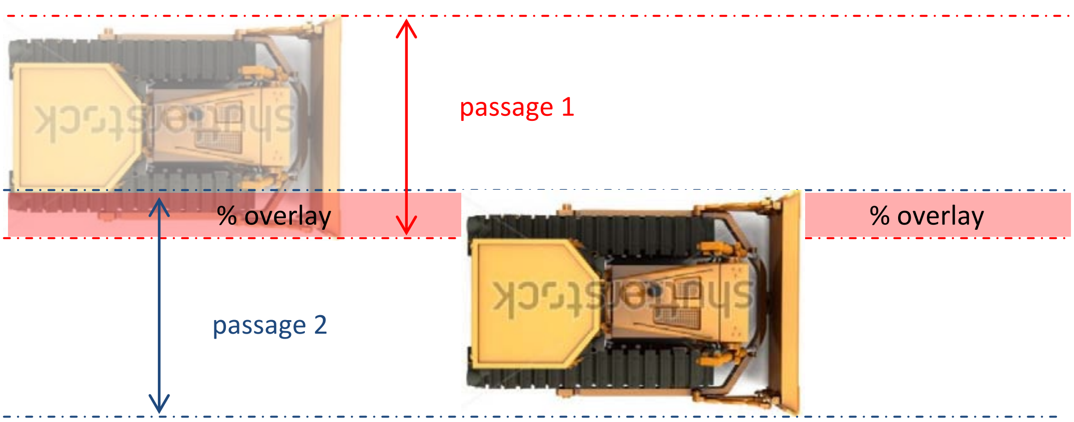

Figure 5: Percentage of overlay representation

If line length increases over l_{max} then the overlay is not annihilating any more the side dump effect and polluted soil is left. The solution to increase l_{max} is increasing the overlay.

d) Key parameters and their interactions

The percentage of overlay and l_{max} are two key parameters which are supposed to affect the efficiency of the remediation process. The threads below illustrate how complex the situation is and how the interactions work.

As we mentioned above, if longer lines are used in the planning, the overlay should be increased to compensate a more important side dump all along the lines. This has several consequences on efficiency:

1. more overlay means more lines per unit of area for the dozer, i.e. less efficiency for moving the same volume of soil.
2. more side dump means waste of energy, because dozer power is used to move contaminated soil on the side (which is not wished), instead of moving it at the end of the line, resulting in an inefficient use of dozer power.
3. longer lines means less dump lines per unit or area, means less route for the excavator, means lower expenses. So with the parameters varying in the same direction we have opposite effect on the efficiency of dozer and excavator use.

From this short analysis we see the complexity of the problem. Those threads are developed by logic and reflection. Experiments will bring concrete element of reflection and qualitative information to confirm the hypothesis made and to support the method development.

e) Hypothesis

1. Shorter lines are more efficient. Planning should favour shorter line pattern.

f) Postulate

2. The go, return and turn practice with bulldozer is the most secure to ensure remediation in any condition.

III. State of the Art Regarding Earthwork Efficiency Optimization

No reference matching narrowly our field of research could be found. Nevertheless a broader research targeting earthwork optimization brought some information of interest.

First we should mention the general method and indications for performance measurement developed in the CATERPILLAR performance handbook 46 (CATERPILLAR, 2016). Few sentences give a good summary of the general idea. “Machine performance must ultimately be measured in unit cost of material moved, a measure that includes both production and costs. Factors bearing directly on productivity include such things as weight to horsepower ratio, capacity, type of transmission, speeds and operating costs.” and “There are other less direct machine performance factors for which no tables, charts or graphs are possible”. We will keep these indications in mind while we will develop the optimization tool and make decision on parameters.

Also optimization of earthworks efficiency has been focused on: (1) equipment allocation for achieving the maximum earthmoving productivity (Cheng, 2010, Cheng 2005, Marzouk 2002, Moselhi 2007, Hess, Conesa-Muñoz 2016, Parente 2014, Shi 1999, Hola 2010); (2) excavator productivity (Halbach 2016, Edwards 2000, Tam 2002); (3) hauling improvement (Chaojue, 2016, Xu 2011) ; (4) least cost for cut and fill operations (Nassar 2012); (5) several tasks optimization (Kataria, 2005) ; and (6) integrated, multi methods and multi objectives optimization of earthwork (Parente, 2016, Zhang, 2008, Marzouk 2004,).

Recently Parente conducted an extensive review and research work on the global optimization of earthwork (Parente et al., 2016). Parente noticed that effective and practical integrated solutions have not been established so far. Solutions exist only for single tasks or partial processes that comprise earthwork (i.e. compaction cycle optimization, excavation cycle improvement). Parente considers earthwork is a complex mechanism where sequentiality and interdependency are noteworthy; and conventional operations research method (linear computing (Murphy. 2005)) is not effective enough for solving global site optimization issues. To this respect he used a couple of technologies like evolutionary computation, data mining (i.e., soft computing), geographic information systems and linear programming in order to achieve the optimization goals. Parente mentions the quality of an earthwork project design depends on the ability to estimate the associated equipment productivity (Parente et al., 2016). For this reason he use evolutionary computation and data mining to first provide realistic estimates of the productivity of available resources and secondly to perform their optimal allocation throughout the construction site (Parente et al., 2016). He employs GIS and linear programming for supporting the optimization of resource and material management, as well as of the trajectories associated with transportation of material from excavation to embankment fronts.

We would like to situate our research work in the light of the information gleaned so far. Similarly to Parente we plan to use a couple of techniques/technologies to efficiently tackle a complex problem where sequentiality and interdependency are noteworthy. The spatial efficiency is resolved using geo-processing and GIS technology (Lucas G., 2016). Efficiency approach through data mining is impossible as no data exists about remediation earthwork. Instead efficiency models for the equipment can be established by calibration approach that can be easily applied in the field. Last, the elementary collaboration issues between equipment can be resolved with linear computing. In the case numerous heavy equipments would be mobilized and work organized on several front, additional optimization with evolutionary computation would be necessary. The frame of this study aims at prefiguring the work organisation at elementary level, linear computing seems sufficient at the moment to tackle the interdependency issues foreseen with the equipment in the remediation work.

Making researches about artificial intelligence and planning of machine automation, we could find several alternatives with the planning. An option is realizing the planning beforehand; it then exposes the plan exploitation to risks and problems because of unforeseen events and different terrain reality. A second option is dynamic planning and real time planning (Barto, 1995, Wang, 2016, Saska 2008, Hess, Halbach 2016, Andrew 1995). They offer more flexibility and immediate correction in the field. This second approach requires an excellent experience about the hazards and problems happening in the fieldwork. As we are paving the way with this topic, we are in a too early stage to consider real time approach. We rather should control precisely x,y and z dimensions and coverage and decided to make a global plan beforehand.

IV. Test of Hypohesis 1: the Increase of Line Lengh Decrease the Collect Efficiency

a) Aims and objectives

This experiment aims at understanding and examining the mechanics of the carriage process.

A first objective is assessing the “reliability” of the carriage. Our objective is to realize a series of measurements in order to be able to evaluate the variance. Our belief is as follow: if variance is low this means the carriage phenomena is reliable (stable and regular); it also strengthens our hypothesis with the possible use of a maximal length.

The second objective is analysing how performance evolve along the track. We are in particular interested in defining and identifying the limit when carriage becomes inefficient.

b) Materials and methods

This experiment is realized with a U-shape blade we designed. The model (LEGO) pushes the material all along the track. We made the experiments with flour for two reasons: 1/we can make clean cut and shape the track very precisely, 2/the clean cut make it easier to take samples every 5 cm. The field with material to excavate is prepared as follow: a rectangle of 11,6 cm width per 165 cm length with a thickness of 3 mm, then 5 mm and finally 8 mm (fig. 6). The material lost and dumped on the side of the track is collected per 5 cm segments (figure 7a and 7b) and weighted with a digital scale with 1 g sensitivity. The sampling distance was chosen short enough in order to have sufficient measurements and long enough in order to be in the measurement range of the digital scale.

Fig.6: Track prepared with floor

In order to have a direct reading of measure of the quantity of material ejected on the sides we have set the width of the material spread on the ground equal with the width of the blade. Consequently there is no inactive material that stays on the side of the system which should be subtracted in the weight measurements.

(a)

(b)

Figure 7: Overview of the track after dozer passage and 5 cm samples

10 repetitions are done for each thickness. 3 different thicknesses are tested. Table 2 presents the plan for the experiment.

Tab.2: Plan for the experiement

Thickness	Thickness scaled to real size (x 16)	Repetitions
3 mm	4,8 cm	10
5 mm	8 cm	10
8 mm	12,8 cm	10

Results

The weight of the material ejected for the three or four first sections was under the detection capacity of the electronic scale. To overcome this problem we have collected the material of the 10 repetitions and made a calculation of the average weight. As a consequence the first four values are not usable in the variance estimation.

The table below summarizes the standard deviation values calculated with 10 repetitions. The standard deviation values are ranging from 0 to 1,43 with an average value of 0,64.

Tab.3: Different deviation results

Mean stand dev. 3 mm	0,5
Mean stand dev. 5 mm	0,58
Mean stand dev. 8 mm	0,84
Mean stand. dev.	0,64
Max. stand. dev.	1,43

Observing the carriage process we made the following qualitative observations:

- The material primarily accumulate in front of the blade evolving in a parabolic profile outstripping the blade.
- The parabolic profile seems to grow horizontally until a limit
- The material accumulation grow up vertically.
- The quantity of material left on the side increase regularly and seems to reach a maximal value.
- When the blade seems filled to capacity, the incoming material get around the accumulated material and is dumped on the side.

The figure 8 below introduces the results of the experiment with the three thickness categories tested. Each point plotted in the scatter is the averaged value for the 10 measurements done (weight of material dumped on the side for the 5 cm sections at the distance indicated in abscissa).

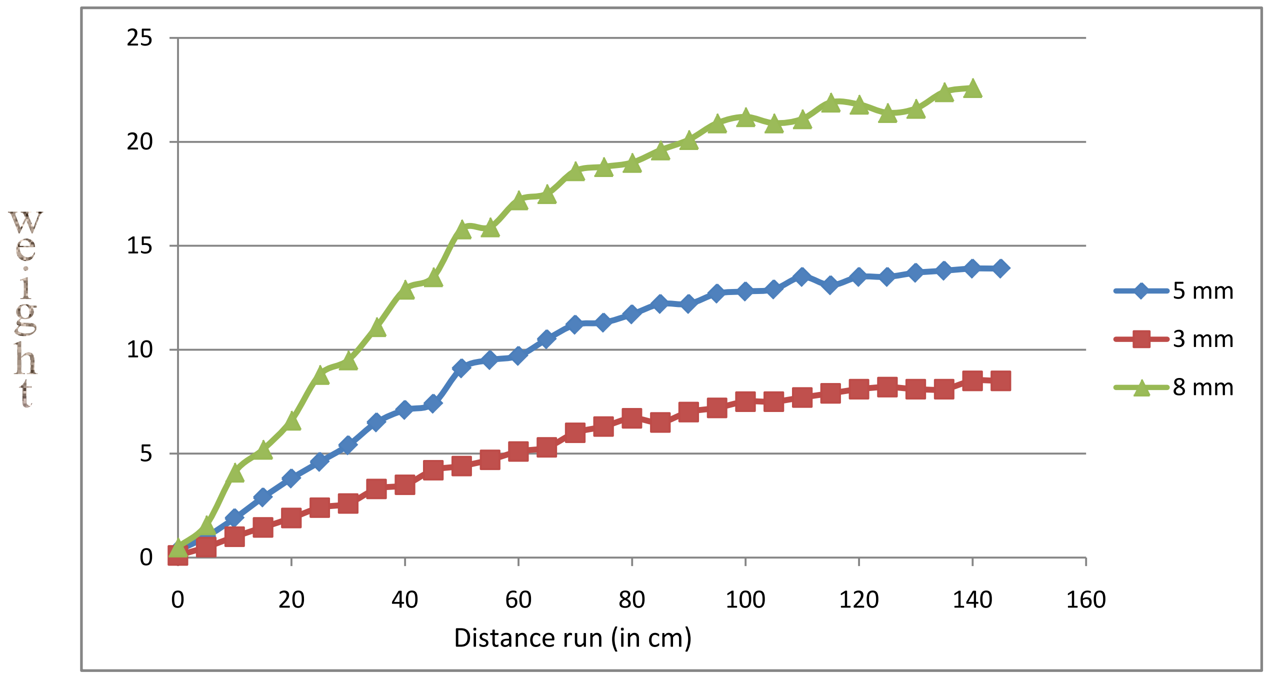

Fig 8: Variation of the average weight ejected on the side with the distance with 3 different thicknesses

Interpretation

The right interpretation of the standard deviation values requires their comparison with the range of the measures (from 2 g to 25 g) and with the sensitivity of the digital scale (1 g). In this respect we excluded the smallest values (< 4g) because the inaccuracy of the measurement is too important compared to the value of the standard deviation. In the case of the remaining values, we can see that the standard deviation is quite low compared to the values. We can conclude that the carriage process is reliable in the range where the measurement inaccuracy becomes negligible. Additionally the regularity of the curves profile we obtained indicates that the repetition number seems sufficient in regards of the variances.

The curve profile confirms the quantitative observations we made. The amount dumped on the sides by the dozer gradually increase until a limit (materialized by the horizontal asymptote of the curve). We suppose that when the blade is filled to capacity all the material moved by the blade is ejected out on the side. Consequently the measurement of the weight of the material on a 5 cm x 11,6 cm section should provide an estimation of the asymptotic value. In order to calculate a precise value we made the weight measurement for a 150 cm x 11,6 cm section for the three different thicknesses and them retrieve the corresponding 5 cm value by making a cross-multiplication . The table below summarizes the results.

Tab.4: Total weight measured for 150 cm and weight calculated for 5 cm with the 3 categories of thicknesses.

Thickness of the layer	Total weight (for 150 cm)	Weight for 5 cm
3 mm	274 g	9,1 g
5 mm	461 g	15 g
8 mm	681 g	22,7 g

At first look, the curve roughly reminds a A.(1 – $e^{\lambda x}$) progression with horizontal asymptotic ending. The consequence is a faster diminution of the equipment performance in comparison with a linear performance progression. This is an important result to consider later on with the planning of the moves of the dozer; shorter push lines would theoretically be advantageous over longer lines.

The following development demonstrates how performance assessment can be done. Considering 8 mm thickness layer, the maximal weight ejected is 22,7 g. When the blade ejects 11,35 g is has already lost 50% of performance. We can see 50% performance limit is almost reached in the first third of the run (with a distance of 35 cm out of a 110 cm maximal run).

Tab.5: Performance estimation using the curve

Thickness	Max ejection	ejection at half performance	Abscissa value at half performance
8 mm	22,7 g	11,35 g	≈ 35 cm
5 mm	15 g	7,5 g	≈ 42 cm
3 mm	9,1 g	4,55 g	≈ 50 cm

The figure below shows how we used the curve to make performance calculation in tab. 5.

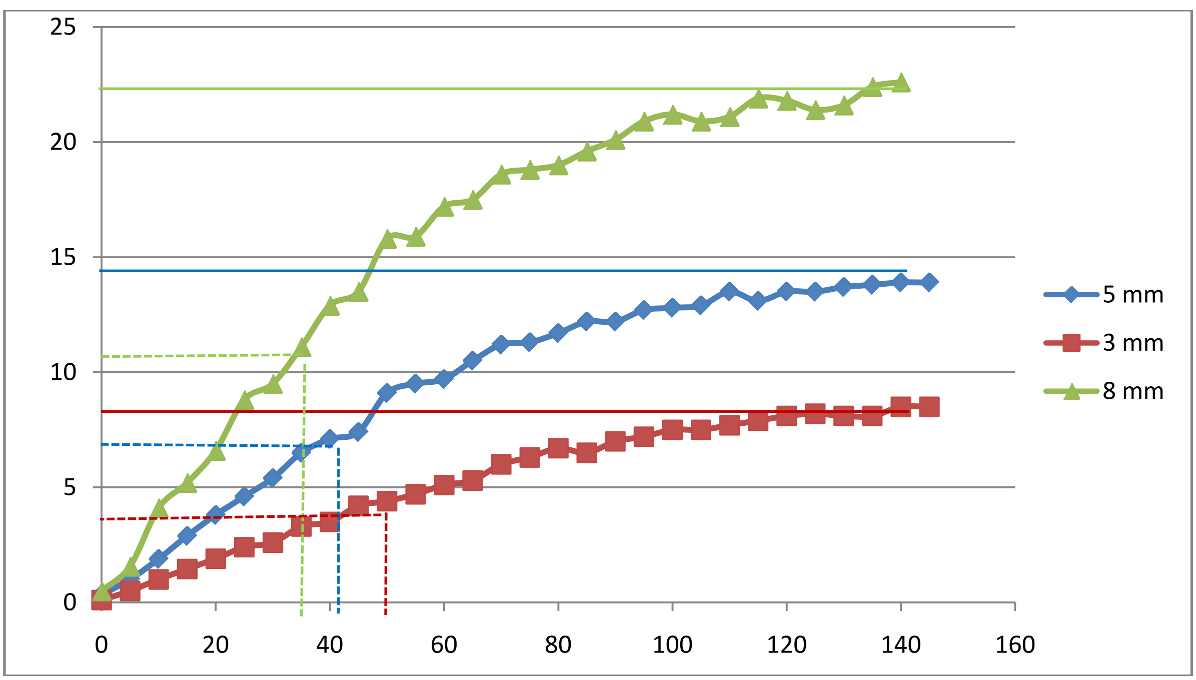

Figure 9: Weight of ejected material

The examination of second partial derivate shows the capacity loss grows proportionally with the distance in a first stage (with $\partial^2 f / \partial x^2 \approx 0$); then the values of the second partial derivate become negative (with positive values for the partial derivate) showing a decrease in the growth of the capacity loss.

The table below provides the value we were able to get with a linear regression with the first part of the curve and specifies the range of the data we used for this.

Tab.6: Results of linear regression made on the first part of the performance curves.

	Distance range	a	b	r
3 mm	0 to 80 cm	0,08	0,23	0,998
5 mm	0 to 70 cm	0,16	0,52	0,996
8 mm	0 to 50 cm	0,3	0,71	0,997

c) Conclusion

With the analysis of the standard deviation between 10 repetitions for 3 x 30 values we first demonstrated that the carriage process is reliable. The reliability makes the planning theoretically possible at model scale.

With the curve profile analysis we demonstrated that a target performance value can be set and the corresponding maximal carriage distance can be determined. As dozers or loaders have to do earthwork with go and return it appear the most efficient strategy is to favour short lines (if only considering dozer). Short lines results in better efficiency as regards to lateral ejection. Longer line results in the ejection of more material. So this first experiment validate our hypothesis. The conclusions drawn here are of fundamental importance for the sustainment of our approach; never the less as it was introduced the performance of the blade is hardly exploitable in the field. Experiment 2 aims at continuing with performance issues consideration, but with parameters (the pair percentage of overlay / maximal length) exploitable in the field and with the planning.

V. Analysing the Relationship Between Overlay and Maximal Line Length

a) Aims and objectives

This experiment aims at testing the effect of the overlay on the maximum carriage distance. In this work the maximal carriage distance is defined as follows: the maximal carriage distance is reached when material start to be ejected on the side of the machine equipment.

b) Materials and methods

This experiment is realized with a U-shape blade. A test consists of 6 contiguous passages with a given overlay so as 5 ejection lines remain on the field. The length of passages is set long enough so as ejection happens on the side of the blade. The distance between the start point and the point where ejection happen is measured. Overlay between passages is increased from 0% to 40% by increment of 5% (tab. 7.).

Tab.7: Experiment plan for overlay test

#	Blade	Overlay in %	Overlay in cm	Number of repetitions
1	U-shape	0	0	10
2	U-shape	5	0,6	10
3	U-shape	10	1,15	10
4	U-shape	15	1,75	10
5	U-shape	20	2,3	10
6	U-shape	25	2,9	10
7	U-shape	30	3,5	10
8	U-shape	35	4,05	10
9	U-shape	40	4,65	10

It is almost impossible to follow perfect parallel lines with the model. A deviation from the theoretical navigation line generates variance with the measurements. In order to avoid the apparition of bias caused by trajectory deviations we decided not to use the wheel loader model. The bucket was mounted on a bridge crane specially designed for the experiment (fig. 10.).

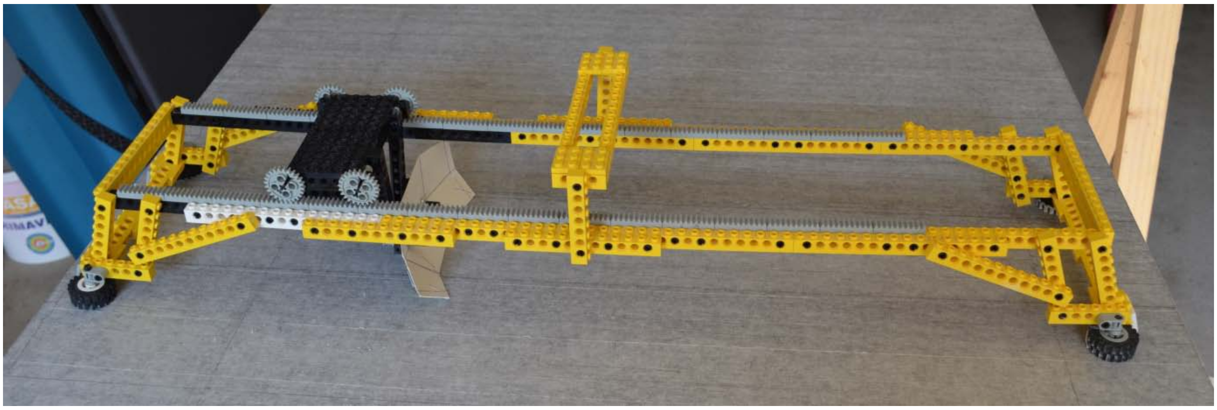

Fig.10: Bucket mounted on bridge crane

A video record of part of the process was prepared and is available online: link here.

Results

Fig.11: Field work after completion of 9 push lines

The results of the measurement are plotted in the figure 4. At first glance it seems the overlay percentage and the maximal push length correlate.

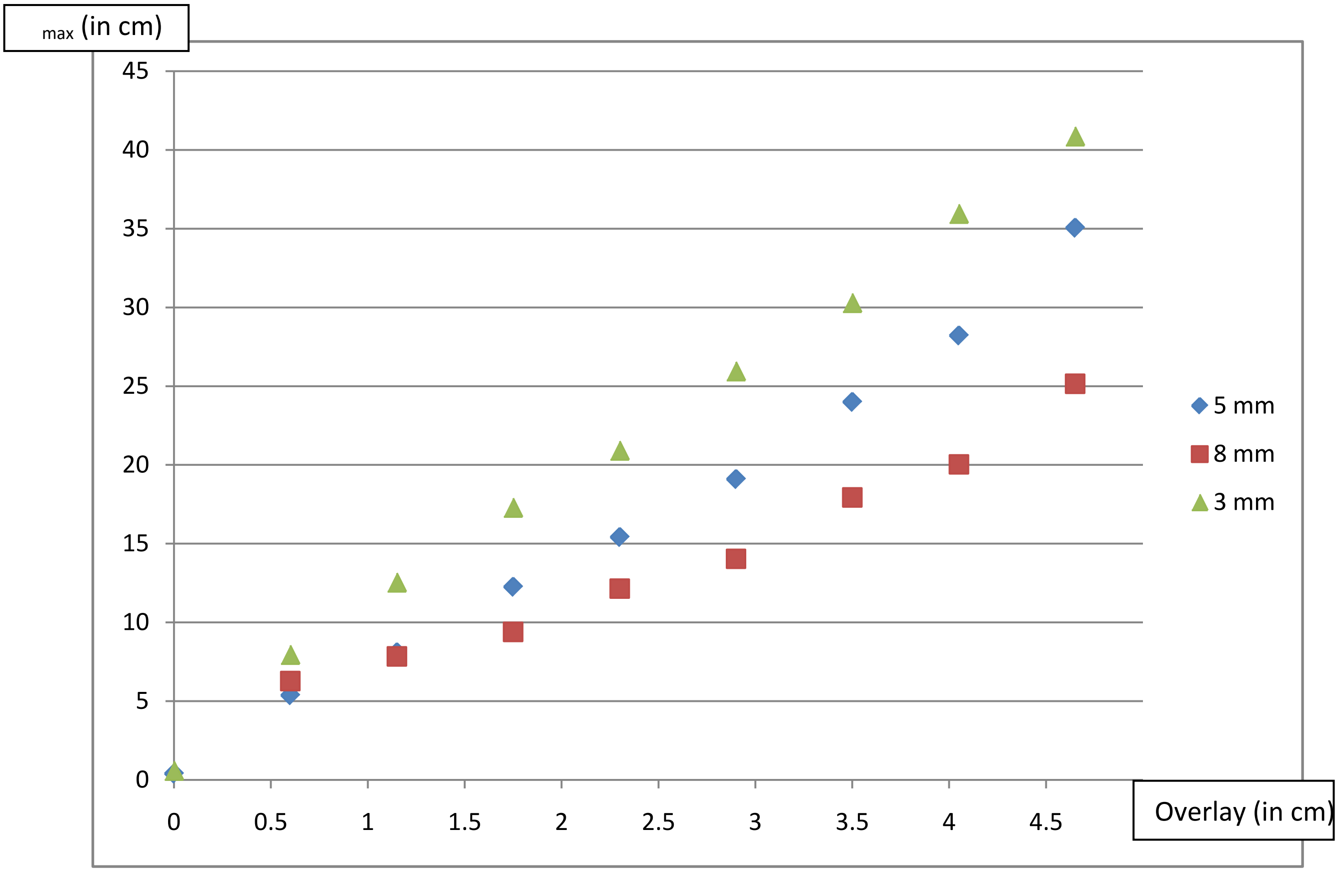

Fig.12

Interpretation

The observations are again characterized by a small variance which shows the reliability of the method/process.

The regularity of the curves shows that sufficient repetitions were done.

The two lowest values collected for the 8 mm test seem located higher than they we would logically expect.

Seeing how points are aligned on the scatter we suggest proceeding with a linear regression.

Tab.8: Results of linear regression

	a	b	r
3 mm	8,31	2,08	0,998
5 mm	7,07	0,028	0,9952
8 mm	4,54	2,26	0,986

The high values with the r coefficient show the overlay correlate well with the maximal length for the three different thicknesses.

c) *Conclusion*

This experiment confirmed that the maximal push length correlate with the overlay between push lines. Moreover as the values with correlation coefficient (r) are satisfying, we can conveniently model the relation between the overlay and the maximal length with linear functions. This experiment also demonstrated the reliability of the measurements/process. It is an important issue in particular if this procedure is used later on as a calibration procedure. In the following developments, the 3 linear functions we calculated will be integrated in a model where the total length run by the different types of equipment will be calculated; then the balance between the lengths (dozer and excavator) will be considered with the aim to optimize the move of the equipment.

VI. Optimization Tool Development and Method Generalisation

a) *Strategy*

We decided to detail how the optimization tool was developed in the case of the dozer / excavator cooperation. A first reason is that it constitutes the most elaborated case. The second reason is the pair dozer /

excavator can be used in any kind of environment and conditions. Last, it is the most common equipment. The cases employing the motor grader and wheel-tractor scrapper are briefly explained afterward.

To develop the tool we started from the beginning of the workflow (earthwork of the dozer) and from the operational and spatial constraint: the whole polluted area should be processed with the appropriate overlay. The overlay is the key parameter and our main variable in this case; it conditions the number of lines per unit of area. So the problem consists in calculating how many passage widths fit into the area width (calculation including a variable overlay parameter) and how many l_{max} fit in the area length (l_{max} also as a variable calculated with the calibration function from the overlay value). Then a second constraint was added to the system to arbitrate the balance between dozer and excavator with their respective "costs". But several questions should be considered when thinking about the balance issue between the costs of dozer and excavator: 1/On which base to make it? 2/What should be part of the cost, what should not be? Regarding 1/ it would not make sense to use hourly costs as we have no input parameter for time; neither we have idea about the time balance for the two different equipment. So the cost should be approached based on (a) volume or (b) based on run distance. Question 2/ help for decision making. Taking the case of the excavator, the volume to collect will remain the same (the volume of the contaminated fraction of soil) whatever l_{max} value is; volume does not vary with the variables. The volume will simply be spread differently in space with more or less dump. So what will vary (as cost to reduce) is the travelling distance for the excavator when visiting more or less dumps lines. So in the case of the excavator the linear cost for the visit of lines makes sense. Is distance also relevant for the dozer too? Yes as far as all the pollution is collected, i.e. spatial coverage is respected. And this is insured by the spatial coverage calculations with the number of line calculation in width and length from geometry and overlay. Additionally, apart the collect work, the dozer should move its own weight on the total distance which is still high in energy consumption and cost as dozer is really heavy equipment. So it makes sense to use linear travel value for optimization. To recapitulate, we only consider the costs varying with the set of variables, and weighting derive from the ratio between the varying costs (cost varying opposite as seen in part 1). Finally, thinking about the comparison of cost for operating bulldozer and excavator moving empty, the cost of the excavator would probably only influence the total cost to a limited extend. This hypothesis should be tested.

b) Details about the calculations

Table 9 introduces all the input parameters and intermediary variables used in the calculation tool.

Tab 9: Cell name inventory (in green)

Input parameters			Max lenght calculation function			
				3	5	8
Area width (m)	Area_width		a	8,31	7,07	4,54
Area length (m)	Area_length		b	2,08	0,028	2,26
Bucket size (cm)	Bucket_width			Table_coef_calc_max_length_from_overlay		
Dozer length (cm)	Dozer_length					
Overlay (percent)	Overlay					
Cost per linear meter dozer	Cost_linear_meter_dozer					
Cost per linear meter excavator	Cost_linear_meter_excavator	Table_linear_costs				
Thickness targetted (mm)	Thickness_targeted					
Line change manoeuvre coefficient	Manoeuvre_coefficient					
Intermediary calculations						
coef dozer	Dozer_coef					
coef excavator	Excavator_coef					
Number of line in width	Line_number_in_width					
Max line length (cm)	Max_line_length					
Number of line in length	Line_number_in_length					
Total route dozer (m)	Total_route_dozer					
Total route excavator (m)	Total_route_excavator					
Total route dozer weighted	Total_route_dozer_weighted					
Total route excavator weighted	Total_route_excavator_weighted					
Sum total route weighted	Sum_total					
Results						
Optimal overlay	Overlay					
Optimal line length	Max_line_length					

The strategy and calculations for each intermediary cell are detailed below.

Coef dozer/coef excavator

The excavator and the dozer are performing two different types of work and we assume they have not the same costs. So the way the two workloads are balanced influences the final cost. If dozer lines are longer, there will be fewer lines to collect for the excavator. So dozer cost increases (because the dozer work plan will contain more overlay and dozer will push on longer so more mass); excavator cost are lowered. Reversely if the dozer makes shorter lines the excavator will have more lines to visit and collect. So excavator moves are increased whereas dozer costs are lowered. So the main question is how can we find the good balance between the two kinds of operations. To solve this issue we have introduced two entry values (one is the cost per linear meter for the dozer, the second is the cost per linear meter for the excavator) and a coefficient is calculated in order to be able to weight the distance run by the two types of equipment. To set the coefficient, we find out which equipment is the most costly (on an linear measurement base) and express how many times it is in comparison of the other.

Number of lines in width

This calculation aims at knowing how many lines cover the width of the work area. The first step in this calculation is to subtract the width of the dozer blade to the width of the work area (fig. 6). Then in the remaining width space we calculate how many tracks (reduced by the overlay value) are fitting. If this number is an integer, then the final number is the division result + 1. If the division result is not an integer, the cell receives the integer of the division +2.

Max line length

This value is calculated using the calibration curves from experience 3. The overlay value is expressed in cm as percentage of the bucket width.

Number of line in length

Similarly to 'number of lines in width' this value, which is not an integer, is obtained by the division of the length of the area by the maximal length on the line.

Total route dozer

This route calculation cumulate the go and return of the dozer. There are 'number of line in length' × 'number of line in width' × 'max line length' for the go, and the same value augmented by a manoeuvre distance value for the change of line. The manoeuvre length is obtained by the multiplication of the dozer length by a manoeuvre coefficient that we expect to be within the range of 1,5 to 2,5 times the dozer's length.

Total route excavator

This total route cumulates the route for collecting the material dumped and the route to join the line oriented in width.

Total route dozer weighted / Total route excavator weighted

These values are the total route calculated above multiplied by the respective coefficients.

Sum total route

The sum of the two weighted routes.

Finally the calculation of the optimal overlay is performed using the Excel solver add-in. Sum_total is set as the objective to minimize. The decision variable is set to "Overlay". The constraints are set as follows: "Overlay <= 40" and "Overlay >= 5".

Calculations are simple in the case of motor grader use. The width of the area should be divided by the width of the blade plus the dump width. As there is no loaded capacity engaged, consequently there is no maximal length calculation nor overlay calculations needed.

The model associated to the scrapper should take into consideration an overlay value between passages. As the scrapper has a capacity value, we consider the same calibration approach could be used to determine the l_{max} / overlay correlation. Calculation sheet has been reviewed to integrate the difference with the geometry.

The different calculation sheets with calculation details are available for download at the following address: put address here.

Exploitation and results

The set of values used to test the effect of parameters on optimization are gathered in table 10. Very interesting observations can be done and interesting conclusions drawn.

Tab.10: Set of parameters for test run

Ref.	Coef dozer	Coef Excav.	Manoeuvre coef	Overlay solver	Total route dozer	Total route excavator
a	1	0	2	30.2	4050m	/
b	1	0	1,5	28.4	3652m	/
c	1	0	0	5	2460m	/
d	1	1	2	32.9	4076m	390m
e	1	0,25	2	31.8	4063m	400m

(a) is considered as the reference scenario. It only uses the dozer, not the excavator. The resulting optimized overlay is 30,2%. In (b) the coefficient for manoeuvre was reduced to 1,5. The optimal overlay decrease by 1,8%. Run (c) (not realistic) tests a run without manoeuvre just for checking if the solver reacts as expected. As expected the minimum overlay 5% is calculated as optimal. The conclusion is manoeuvre move represent an important part of all the moves and it should really be considered. Run (d) introduce the excavator in the optimization calculation with a coefficient equal to the dozer (strong in regards of reality). Overlay increase by 2.7% (so it is quite limited). Scenario (e) tests a much more reduced ratio (which is aimed at being closer to reality) between the dozer and excavator. Difference with overlay is 1,1% and total dozer route varies less than 0,5%.

The figure below shows how the total route varies with the overlay in the case of the dozer (blue series) (coef dozer = 1, coef. excavator = 0). Several observations can be done. The first observation is that evolution is not linear and a minimum can be observed in the middle part of the curve at 30,2%. Comparing the smallest overlays (<15%), the total route variation is very important. For overlay over 20%, the route varies much less. In this situation, it is more efficient to perform more important overlays. This situation is caused by the effect of the length of the turn manoeuvre. The green series represents the route without manoeuvre, so the difference between the blue and the red series is the manoeuvre effect. When the lines are short (and overlay is small) the change line manoeuvre becomes a significant percentage of the total route which decreases the efficiency of the moves of the dozer. Over 20% overlay, the total route variation only varies by 6%. On one hand 6% is significant; on the other hand with the perspective of optimization it is not that much.

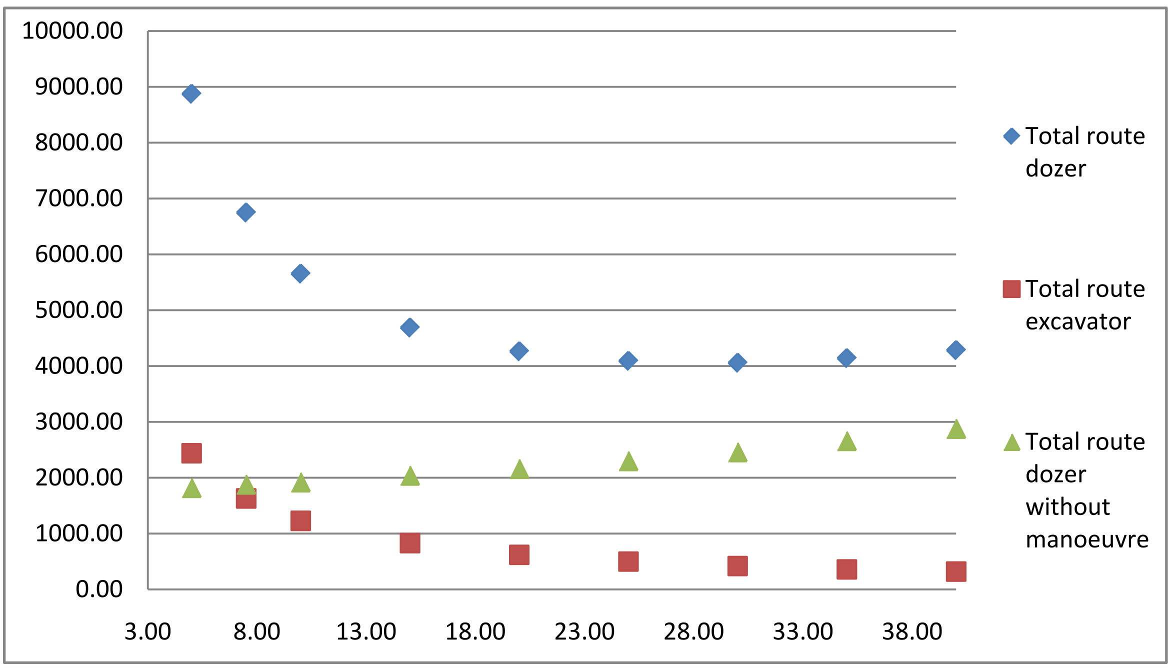

Fig.12: Evolution of total distance for the equipment in function of the overlay.

Last, the red series figures how total route for the excavator varies with the overlay. Variation has not a linear shape and decrease when overlay increase. In consequence the optimization of the combined use of the two equipments is located a bit above the minimum of the blue series. It satisfies almost the minimum value for the dozer and a minimal value for the excavator. As the excavator curve decrease more than the one of the dozer increase, it logically favour the excavator, that's the reason why the optimal overlay is a bit above the minimum value for the blue curve.

VII. Discussion

The experiments are done with scale models. This raises the following fundamental question: are all the results transferable from the 1:16 scale to 1:1 scale? Our beliefs are as follows: the complete method is transferable whereas the sets of optimized parameters calculated at 1:16 are not. The method is applicable at 1:1 scale because the physical basis generally works the same for the scale model and for the equipment in the field (forces, volume capacity, input/output balance with the bucket, spatial coverage, etc.). The optimized parameters are not robust for scale transfer (the balance of forces differs from model to 1:1 scale (friction, forces values, excavated material characteristics are different). The calibration method should be applied in the field with the equipment, data extracted and processed to extract terrain situation values for the pair overlay / l_{max}.

The method we set up works on simple basis and it can easily be implemented in the field. A navigation plan has to be set with for example 8 lines. The overlay between the passages can be increased by

5% from 0 to 40% from line 1 to line 8. Then I_{max} is measured and associated to the different overlays. This calibration has to be done for: 1/ the different thickness that should be implemented, 2/ the different bucket that will be used. We do not see any usefulness to model the parameters variation based on thickness variation and rather propose to perform a case-by-case calibration.

In the geo-processing model we built the overlay parameter does not exist; but still it can be solved. The geo-processing tools should be run with a parcel width of bucket_width × (1 – overlay). This way the field implementation will be larger by ½ overlay on each side compared to the plan, establishing the desired overlay.

The homogeneity of terrain should be assessed and the impact on equipment efficiency assessed as well. It is important to know if it is worth doing diverse calibrations to get different sets of optimized parameters for the different soil types.

Overlay value is expressed as a percentage the blade width. This means calibration has to be done for any blade type use in the field. This is not practical because lot a calibration needed.

Coefficients for dozer and excavator should primarily come from expert estimates. It is not the most accurate but it is worth for a start. Then, when operational data will be available (from the tracking done with positioning equipment) data mining should be used to extract more accurate data. From this, the set of parameters can be recalculated. Many sources mentioned the efficiency of data mining technique to have realistic assessment of equipment efficiency/costs (Parente, 2016, etc).

Optimization of the spatial coverage requires having minimal overlay between passages and minimal overlay is possible only if the lines are short. So first conjecture is optimization should favour the shortest lines. But using appropriate parameters and modelling we demonstrated short lines are counterproductive because of the “cost” of manoeuvre. Consequently the calculated optimal line is shifted to a higher value. And the value is shifted even a bit higher when the excavator travel costs optimization are integrated. We ended up with two extreme overlay values of 30,2% (excavator not integrated) and 32,9% (excavator dozer balance of 1/1) which are quite close each over. Excavator effect in optimization exists, but is limited.

Decision making is a complex process in the case of soil remediation. Many factors should be considered (like the remediation efficiency objective, time constraint, soil characteristics, thickness to excavate, equipment available) to select, adapt and even develop the appropriated remediation approach. It is not possible to cover this topic exhaustively (and obviously as we were sorting things out) but we have tried to the extent of possible to make a coherent approach, with classical operational basements. We also attempted to widen the implementation possibilities and provide threads in varied directions. The next research work will focus on technical proposal for machine navigation, machine control (including grading control) in order to precisely met remediation objectives and excavate only polluted soil. When this last part will be set up, industry will have at disposal a complete and coherent approach for precision excavation implementation.

VIII. Conclusion

Bibliographic research on our specific topic has not brought relevant information. Paving the way, we sometimes had to introduce and develop our own vocabulary and concepts. Occasionally we could get inspired by existing work from the field of earthwork optimization.

The experiment on collect efficiency made with a scale model of dozer confirmed the hypothesis: collect efficiency decrease all along the path while the bucket gets filled and while lateral ejection increase to a maximum.

The calibration approach tested with scale model was successful. It allows correlating overlay with maximal line length. We believe it is replicable in the field with the equipment with a simplified protocol (as many measurements are necessary) to measure overlay/I_{max} values and to be able to build calibration curves.

Optimization tool was developed around a first set of key parameters: overlay and I_{max} value, linear computing and the use of a solver tool. Trying different test scenarios with different parameters combination it turned out not only overlay and I_{max} are of critical importance, but also the length of manoeuvre for line change. The tool definitely helps to test many variations and to rationalise decision making regarding overlay strategy, effect of manoeuvre and effect of equipment on costs. It clearly showed the limited interest of excavator cost integration in the optimization process (total run distance changes between scenarios inferior to 1%), but on the opposite clearly showed the important effect of manoeuvre on total distance (0,5 pont change with manoeuvre generate 1,8% change with overlay and 10% change with total distance). Taking the full range (5 to 40%) of overlay, the total distance varies very much 119%. Taking only the values over the optimum a 10% variation of overlay produces only 6% of variation with the total length.

After the run of the solver, two parameters should be used in the geo-processing tool we formerly designed for work planning: the overlay (parcel width = bucket_width × (1 – overlay)) and the maximal line length (parcel length = maximal length).

Further optimization of remediation work is possible by employing the techniques described in the literature, in particular fleet balancing techniques.

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Future work will consist in making proposal with equipment for machine navigation, machine control (in particular grading control) to achieve grading and excavation precisely.

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