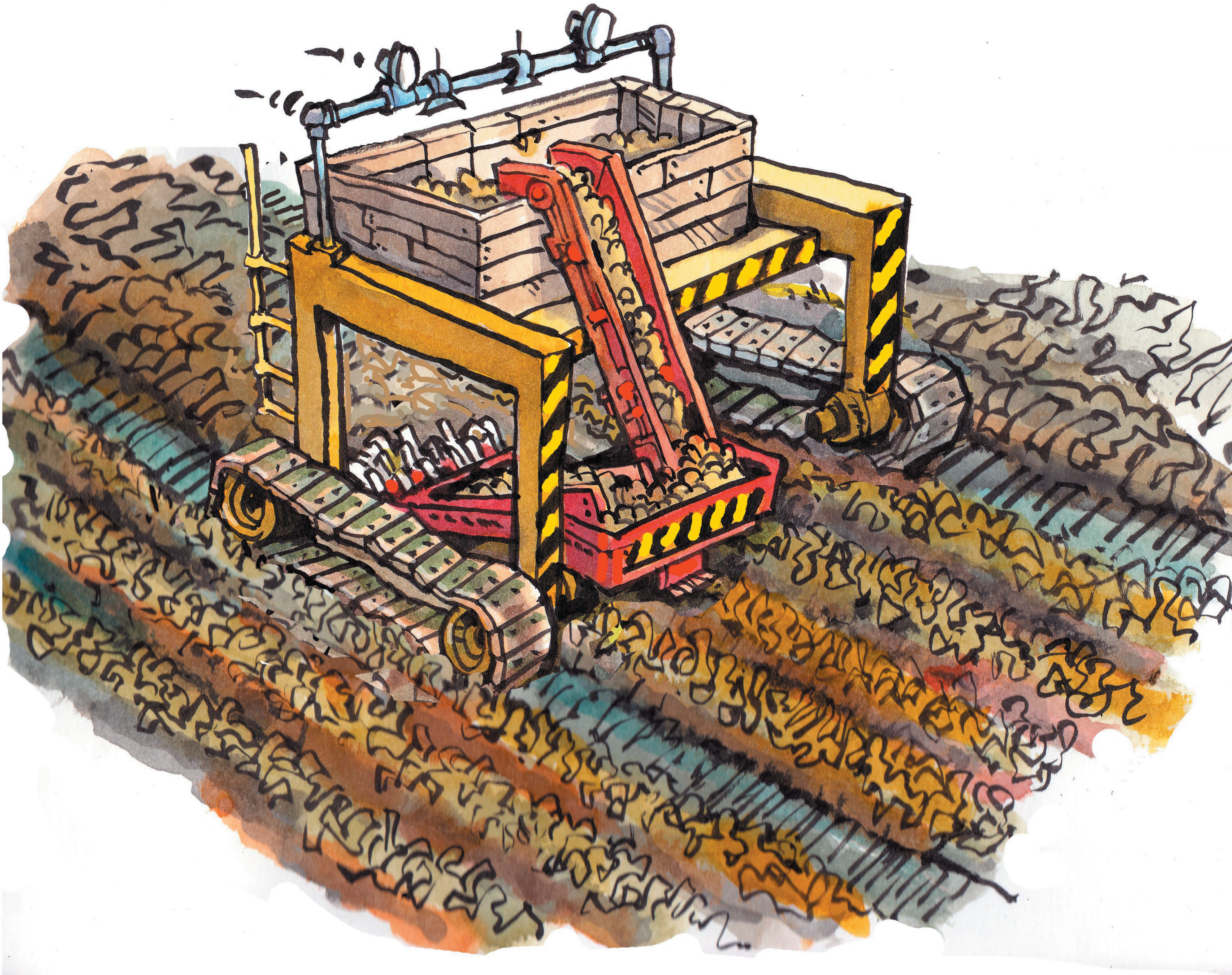

# Model based performance analysis of a light weight autonomous potato harvester

P. van Dalfsen | A. van 't Ooster | J.A. Booij | M.P.J. van der Voort | A. Veldhuisen
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# Model based performance analysis of a light weight autonomous potato harvester

Feasibility study of lightweight, autonomous potato harvest strategies by means of model experiments

P. van Dalfsen, A. van 't Ooster, J.A. Booij, M.P.J. van der Voort, A. Veldhuisen, A.T. Nieuwenhuizen, J.A.L.M. Kamp[1]

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This study was carried out by the Wageningen Research Foundation (WR) business unit Field Crops and was commissioned and financed by Topsector Agri & Food as part of the SMARAGD project (AF-16190).

WR is part of Wageningen University & Research, the collaboration of Wageningen University and Wageningen Research Foundation.

Wageningen, May 2021

Report WPR-882

WAGENINGEN
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Dalfsen, P. van, Ooster, A. van 't, Booij, J.A., Veldhuisen, A., Nieuwenhuizen, A.T., Kamp, J.A.L.M, 2021. *Model based performance analysis of a light weight autonomous potato harvester; Feasibility study of lightweight, autonomous potato harvest strategies by means of model experiments.* Wageningen Research, Report WPR-882.

This report can be downloaded for free at https://doi.org/10.18174/563388

Summary: This study aimed to determine the feasibility of a lightweight autonomous potato harvester operating in a controlled traffic farming system by conducting a model-based performance analysis of concepts for this system and comparing this with the performance of conventional harvesting systems. The entire harvesting and transport process was modelled with the use of discrete event simulation. This report shows that the value proposition with mobile field robotic solutions is a viable option to overcome the challenges of current oversized harvest machinery.

Keywords: control traffic farming, discrete event simulation, harvest logistics, autonomous harvest



Chamber of Commerce no. 09098104 at Arnhem
VAT NL no. 8065.11.618.B01



Report WPR-882

Photo cover: artist impression autonomous harvester by Henk van Ruitenbeek

# Contents

# Preface

Dutch agriculture can be characterized by its high performance with respect to yields and labour efficiency. Enabling factors are highly qualified farmers, up-to-date mechanization and a growing economy of scale at farm level. The scale increase relates to the fast-growing size of the farms and bigger field sizes. In the farmers' mind soil compaction is considered to be an important yield reducing factor. Control Traffic Farming (CTF) is perceived as an interesting alternative for current farming systems. By driving only on fixed traffic lanes, the cropping bed is spared. However, the downside of these systems is a reduced level of flexibility in the work execution, leading to a lower efficiency and a higher cost price. That is why farmers are looking with interest at new autonomous platforms that are often light-weight and seem to be very suitable for use in these CTF farming systems.

Nowadays, autonomous platforms are under development and doing measurements on these systems is currently not possible. Fortunately, simulation of these new systems is possible thanks to a good simulation model that has been developed within the Farm Technology Department of Wageningen University & Research. This report provides an interesting comparison of the productivity of existing mechanisation versus new autonomous systems for potato harvesting and product transport. It shows that new lightweight autonomous systems can compete with the large and heavy systems that now prevail in practice.

Besides thanking the researchers who worked on this report, I would also like to share special thanks to the Master students Biosystems Engineering, especially Xavier Hartmann and Stijn Bomers, as well as their supervisor Bert van 't Ooster, for building and improving the simulation model. Without this hard work, this study would not have been possible within this time frame.

Jan Kamp,
Project manager Smaragd

# Summary


Larger and heavier machinery in arable farming takes its toll due to declining soil quality and biodiversity, soil compaction, vulnerability and lagging yields. Technological solutions offer opportunities for small-scale smart solutions that prevent soil damage and save labour. This includes the application of multiple autonomous lightweight vehicles, a tramline system, monitoring techniques for weed and disease recognition, and location-specific treatment. Another development is the emergence of mixed and strip intercropping which can lead to improved utilization of light, water and a smaller and reduced chance of diseases and pests with higher yield of up to 22% (Yu et al., 2015) as a result.

One of the goals of the Smaragd project was to develop a feasible concept for harvesting large volumes of root crops, such as sugar beet, potato, onion and winter carrot with minimal impact on soil quality. This study aimed to determine the feasibility of a lightweight autonomous potato harvester operating in a controlled traffic farming system by conducting a model-based performance analysis of concepts for this system and comparing this with the performance of conventional harvesting systems. Discrete Event Simulation (DES) was used in which the entire harvesting process was modelled. A field of 6 hectares (200 x 300 m) at 1 km from the farm was used as a basis. Various concepts of the harvesting system were simulated including 4 conventional harvesting methods: 1) 4-row self-propelled harvester – continuous unloading in a tipper while driving; 2) 2-row trailed harvester without fixed tramlines – continuous unloading in a tipper while driving; 3) 2-row trailed harvester with fixed tramlines - unloading in tipper at headland; and 4) 2-row trailed harvester with fixed tramlines, which unloads into mobile crates. As a Smaragd solution, 4 small-scale lightweight and autonomous concepts with have been simulated: 5) 1-row harvester with 100 kg buffer; 6) 1-row harvester with 500 kg buffer; 7) 2-row harvester with 100 kg buffer; 8) 2-row harvester with 500 kg buffer. In comparing simulation results with different input parameter values, the aim was to realise a high field efficiency of the harvesting system and therefore minimized waiting time for the harvester.

The initial expert estimation of input parameter values for the Smaragd concepts showed very long waiting times for the harvester. Therefore, a sensitivity analysis was carried out for a number of parameters with expected high impact on the efficiency of the harvester: buffer capacity of the harvester, the buffer trigger level for calling a transport unit, the number of transport units and the transport capacity of the transport units. The buffer level and buffer capacity turned out to be particularly relevant. In all simulations, the optimum number of transport units with storage capacity suitable for the harvester was two. Further simulations showed that the stacking of input parameters had a clear effect on the efficiency of the Smaragd concepts. With this, the waiting time of the harvester for processing the model field (6 hectares) could be minimized to 0.4 hours in the Smaragd - 1-row harvester concept and to 1.4 hours in the Smaragd 2-row harvester concept. This enabled a gross harvesting capacity of 0.29 and 0.41 hectares per hour, respectively. The stacking effect has also been investigated with the conventional concept "4-row self-propelled harvester - continuous unloading in a tipper driving next to the harvester". This showed that the process was already efficient and efficiency improvement (from 65% to 76%) was only possible with greatly increased bunker and transport capacity whereby the waiting time of the harvester was reduced from 1.0 hour to 0.0 hour. The gross harvesting capacity was 0.86 (basis) to 1.01 (optimized) hectares per hour.

An economic evaluation showed that based on model outcomes and cost estimates the Smaragd mechanisation strategies were cheaper than conventional strategies. In particular, the mechanisation costs are much lower with the Smaragd concepts than with the conventional concepts. The costs and depreciation of the Smaragd concepts were estimates, as this solution does not exist yet. The labour costs of the Smaragd solutions are higher than conventional because the total operating time of the Smaragd concepts on the 6 hectares field was higher (20.81 hours for the 2-row harvester, 14.77 hours for the 1-row harvester, and 6 hours for the conventional 4-row harvester) and the number of employees required was estimated. The results of the economic evaluation showed that small lightweight harvesting operations can compete with conventional mechanisation strategies and that the economic feasibility of the Smaragd

concepts is very likely if they operate as reliable as assumed in the simulations. The capacity of the Smaragd solutions is significantly lower. The optimized Smaragd scenario, 2-row with 500 kg buffer, requires 2 harvesters to match the capacity of the self-propelled 4-row harvester. If the costs of the optimized Smaragd scenario are doubled the costs are still lower as the self-propelled harvester. Additional simulations with the model of these options will be needed.

# Samenvatting

In de akkerbouw is al jaren sprake van schaalvergroting. De steeds grotere en zwaardere mechanisatie begint haar tol te eisen door teruglopende bodemkwaliteit en -biodiversiteit, bodemverdichting, een toegenomen kwetsbaarheid en achterblijvende opbrengsten. Technologische ontwikkelingen bieden kansen om tot kleinschalige/slimmere oplossingen te komen, die bodem en arbeid sparen. Denk hierbij aan toepassing van meerdere autonome, kleinschalige en lichte voertuigen die samenwerken, rijpadensysteem, meettechnieken voor o.a. onkruid- en ziekteherkenning, en plaats specifieke behandeling.

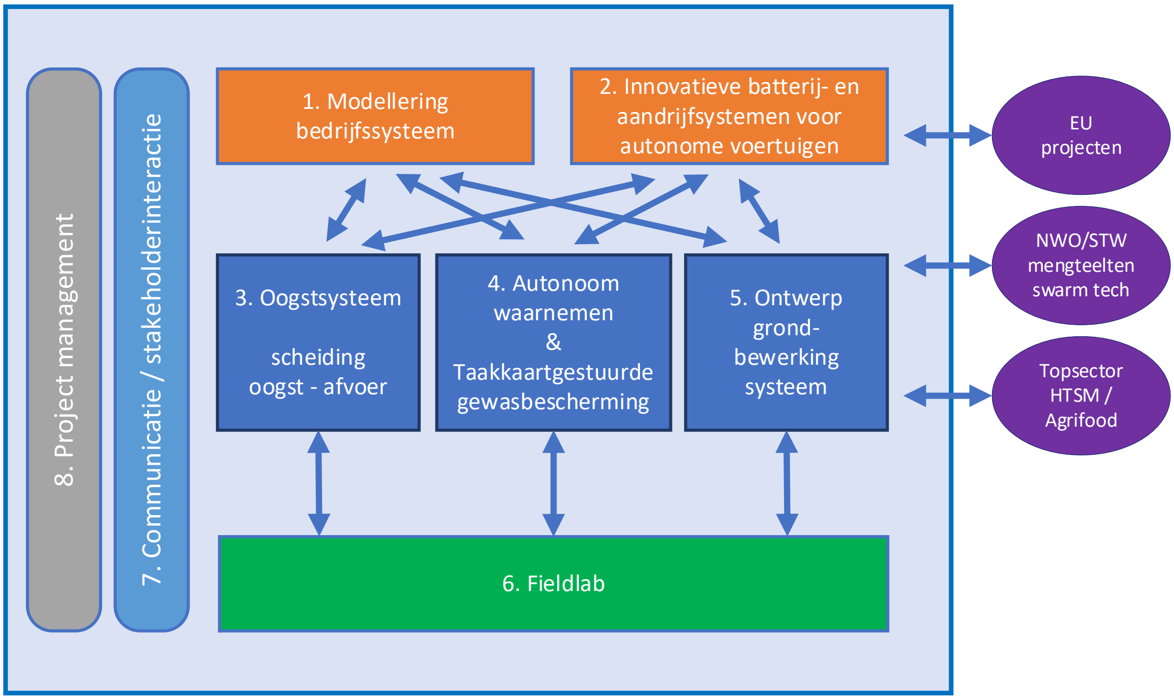
Een andere ontwikkeling is de opkomst van meng- en strokenteelten (mixed cropping en intercropping). Bij meng- en strokenteelten wordt niet meer op één uniform perceel één enkel gewas geteeld, maar staan gewassen in stroken door elkaar op het perceel of tezamen in rijen op bij voorkeur onbereden bedden. Dit kan leiden tot verbeterde benutting van licht, water en mineralen en verminderde kans op ziekte- en plagen met hogere opbrengsten als gevolg. In een recente meta-analyse van de internationale literatuur door WUR (Wageningen University & Research) en INRA (Institut National de la Recherche Agronomique) over intercropping komt een gemiddelde opbrengstverhoging naar voren van maar liefst 22% (Yu et al., 2015).

De zoektocht in de PPS SMARAGD (Slimme Mechanisatie – Automatisering – Robotisering voor een Akkerbouw met Groei en Duurzaamheid) richt zich op een synergie tussen teelttechnische aanpassingen en kleinschalige lichte en autonome technologie voor het uitvoeren van bewerkingen. Deze combinatie moet fijnmazige teelt toepasbaar maken op professionele, grootschalige akkerbouwbedrijven. SMARAGD is gericht op opbrengstverhoging, verlaging van milieuschade door gewasbeschermingsmiddelen, verbetering van nutriënten-efficiëntie, energiebesparing en arbeidsoptimalisatie. In het SMARAGD project werken bedrijven en onderzoekers samen aan de ontwikkeling van hightech systemen om dit nieuwe landbouwconcept dichterbij te brengen. Een landbouwconcept dat een oplossing moet bieden voor de verslechtering van bodemkwaliteit en de kansen moet benutten die meng- en strokenteelt potentieel bieden. Het richt zich op de teelt van hoog salderende akkerbouw- en vollegrondgroente gewassen.

De werkpakketstructuur van SMARAGD is weergegeven in figuur 1. Dit rapport komt voort uit de werkpakketten modellering bedrijfssysteem (1) en ontwerpen en realiseren van een autonoom oogstsysteem voor een rijpadensysteem (3). Naast het oogstsysteem wordt gewerkt aan innovaties in elektrische aandrijfsystemen en batterij managementsystemen voor autonome voertuigen (2), het ontwikkelen van autonoom waarnemen van onkruiden en ziekten, taakkaart gestuurde gewasbescherming (4) en het ontwikkelen van een grondbewerking passend binnen een rijpaden-systeem (5). De prototypes en ontwikkelingen voortkomend uit ontwerptrajecten binnen de werkpakketten 3, 4 en 5 worden getest, geëvalueerd en doorontwikkeld onder praktijkomstandigheden in een Field Lab.

Ontwerpen van het oogstsysteem: Het doel van werkpakket 3 is het ontwikkelen van een haalbaar concept voor het rooien van grote volumes rooigewassen, zoals suikerbieten, aardappelen, uien en winterwortelen met een minimale bodembelasting. In een rijpadensysteem met onbereden stroken gebruiken de rooier en het transportvoertuig dezelfde rijpaden. De dimensionering van deze voertuigen moet passen bij deze situatie. Dit onderzoek had als doel de haalbaarheid een lichtgewicht autonome aardappelrooier te beoordelen door een modelgebaseerde prestatieanalyse van een lichtgewicht autonome aardappelrooier uit te voeren en die te vergelijken met conventionele rooisystemen. In dit onderzoek is gebruik gemaakt van 'Discrete Event Simulation' (DES), waarbij het hele rooiproces is gemodelleerd. Als basis is een fictief perceel gebruikt van 6 ha (200 x 300 m) op 1 km afstand van de boerderij. Hiervoor zijn verschillende concepten van het rooisysteem gesimuleerd, waaronder 4 conventionele rooimethoden:

1. 4-rijige zelfrijdende rooier – continu lossen in meerijdende kipper
2. 2-rijige getrokken rooier zonder vaste rijpaden – continu lossen in meerijdende kipper
3. 2-rijige getrokken rooier met vaste rijpaden - lossen in kipper op kopakker
4. 2-rijige getrokken rooier met vaste rijpaden, die lost in meerijdende kratten




***Figuur 1*** *Samenhang werkpakketten in SMARAGD.*

Als Smaragd-oplossing zijn 4 varianten met kleinschalige lichte en autonome technologie gesimuleerd:

1. Smaragd – 1-rijige rooier met 100 kg buffer
2. Smaragd – 1-rijige rooier met 500 kg buffer
3. Smaragd – 2-rijige rooier met 100 kg buffer
4. Smaragd – 2-rijige rooier met 500 kg buffer

Bij de vergelijking van de concepten is gefocust op een hoge efficiëntie voor de rooier en dus weinig wachttijd voor de rooier, om een zo hoog mogelijk veldefficiëntie te realiseren en optimaal gebruik te maken van de werkbare dagen.

Bij de eerste inschatting van input parameters voor de Smaragd varianten door expert-onderzoekers bleek dat er lange wachttijden voor de rooier ontstonden. Vervolgens is er een gevoeligheidsanalyse uitgevoerd naar een aantal parameters, waarmee de efficiëntie van de rooier naar verwachting verhoogd kon worden, zoals buffercapaciteit van de rooier, het bufferniveau waarbij de volgende transportunit wordt opgeroepen, het aantal transporteenheden en de transportcapaciteit van de transporteenheden. Hiervan bleken vooral het bufferniveau en de buffercapaciteit grote relevantie te hebben. In alle simulaties bestond het optimum transport uit 2 transporteenheden met opslagcapaciteit passend bij de rooier. Op basis van oriënterende simulaties is gebleken dat het stapelen van inputparameters een duidelijk effect heeft op de efficiëntie van de Smaragd-concepten. Hiermee kon de wachttijd van de rooier voor het rooien van het modelperceel van 6 ha geminimaliseerd worden tot 0,4 uur in het concept van Smaragd – 1-rijige rooier en 1,4 uur in het concept van Smaragd 2-rijige rooier. Hiermee kon respectievelijk een bruto rooicapaciteit behaald worden van 0,29 en 0,41 hectare per uur.

Ter vergelijking is ook bij het conventionele concept '4-rijige zelfrijdende rooier – continu lossen in naast rijdende kipper' het stapeleffect onderzocht. Daaruit kwam naar voren dat het proces al heel efficiënt verloopt en alleen met sterk verhoogde bunker- en transportcapaciteit efficiëntieverbetering mogelijk is (van 65% naar 76%), waarbij de wachttijd van de rooier werd verminderd van 1,0 uur naar 0,0 uur wachttijd. De bruto rooicapaciteit lag op 0,86 (basis) tot 1,01 (geoptimaliseerd) hectare per uur.

Uit een economische verkenning van de mechanisatiestrategieën van Smaragd blijkt dat deze op basis van modeluitkomsten en kostenraming goedkoper zijn dan conventionele mechanisatiestrategieën. Met name de mechanisatiekosten zijn bij de Smaragd-concepten lager dan bij de conventionele concepten. De kosten en de afschrijving van de Smaragd-concepten zijn schattingen, aangezien deze oplossing nog niet bestaat. De arbeidskosten van de Smaragd-oplossingen zijn hoger dan conventioneel omdat de totale bedrijfstijd van de Smaragd-concepten op het 6 ha perceel hoger ligt (20,81 uur voor de 2-rijige rooier, 14,77 uur voor de 1-rijige rooier en 6 uur voor de conventionele 4-rijige rooier) en het aantal in te zetten medewerkers nog ruim is ingeschat. De resultaten van de economische evaluatie laten zien dat de kleine lichtgewicht oogstoperaties kunnen concurreren met conventionele mechanisatiestrategieën en dat de economische haalbaarheid van de Smaragd-concepten zeer waarschijnlijk is als deze zo betrouwbaar werken als is aangenomen in de simulaties. De capaciteit van de Smaragd oplossingen ligt wel aanzienlijk lager. De geoptimaliseerde Smaragd-oplossing, 2-rijer met 500 kg buffer, vergt ongeveer 2 rooiers per perceel. Het verdubbelen van de kosten per hectare geeft nog steeds lagere kosten per hectare. Verdere modelstudie van deze opties zijn wenselijk.

# 1 Introduction

Arable farming has been increasing in scale for more than 50 years using increasingly large and heavy mechanisation. Large and heavy mechanisation not only increases efficiency but also causes problems like declining soil quality and biodiversity, soil compaction, increased vulnerability and lagging yields. Technological developments offer opportunities to come up with smart small-scale solutions which alleviate these problems with acceptable labour demand. These opportunities include the use of autonomous, small-scale and light vehicles (swarms), techniques for sensing, analysis and control (ai), and Controlled Traffic Farming (CTF).

CTF is a farm management principle that restricts all movement of vehicles to fixed tram lines. CTF itself does not solve the problem with soil compaction. The heavy machinery still causes soil compaction, but now mainly in the tram lines, leaving the soil in between the tram lines unaffected. This results in better workability of the soil and an increased crop yield in the strips between the tram lines. Although compaction is concentrated in the tram lines, the compaction radiates outwards into the bed, reducing soil quality and yield near the tram lines. Tracks instead of wheels, or smaller and lighter machines might be a solution, but then we need to understand how the compaction radiates through the soil, and how more frequent passes of lighter machines affect soil compaction. Besides the negative effect of soil compaction near the tram lines, plants near the edge of crop strips receive more sun light and have access to more nutrients, because of absence of crop in the tram lines. It is unclear how much different crops benefit from this.

Another development is the use of intercropping. With mixed and strip intercropping as opposed to sole cropping where a single crop is grown on a single uniform field, crops are grown in strips mixed together within one field or in rows mixed within (preferably unpaved) beds. The improved use of light, water and minerals and opportunities for disease and pest control has potential to lead to higher yields. A recent meta-analysis of international literature by WUR (Wageningen University & Research) and INRA (Institut National de la Recherche Agronomique) on intercropping reveals an average yield increase of no less than 22% (Yu et al., 2015). Combining intercropping with smart light weight autonomous machines for crop operations may benefit both the arable farmer and the agro-ecosystem.

## 1.1 SMARAGD project

The PPS SMARAGD (Smart Mechanisation - Automation - Robotisation for Arable farming with Growth and Sustainability) aims to develop small-scale light and autonomous technology in order to allow for a fine-meshed cultivation that is applicable to large-scale professional arable farms. The fine-meshed cultivation in turn aims to realise increased yields, reduced environmental impact caused by crop protection agents, improved nutrient efficiency, improved energy efficiency and reduced labour demand.

In the SMARAGD project, companies and researchers worked on the development of high-tech systems to realise a new agricultural concept. This high-tech system design covers all crop operations, seeding/planting, crop care and harvesting. This concept should offer a solution for the deterioration of soil quality and exploit the potential offered by intercropping. The project focuses on the cultivation of high-balance arable and outdoor vegetable crops in which heavy large-scale mechanisation is replaced by light, autonomous, innovative technologies.

The work package structure of the project is shown in Figure 2. This report is part of the work packages farm system modelling (1) and autonomous harvesting system design (3). In addition to the harvesting system, work is being done on innovation in electric drive systems and battery management systems for autonomous vehicles (2), the development of autonomous detection of weeds and diseases, task-map-driven crop protection (4) and the development of a retaining tillage system that fits a tramline system (5). The prototypes and developments arising from work packages 3, 4 and 5 are tested, evaluated and further developed under practical conditions in a Field Lab.

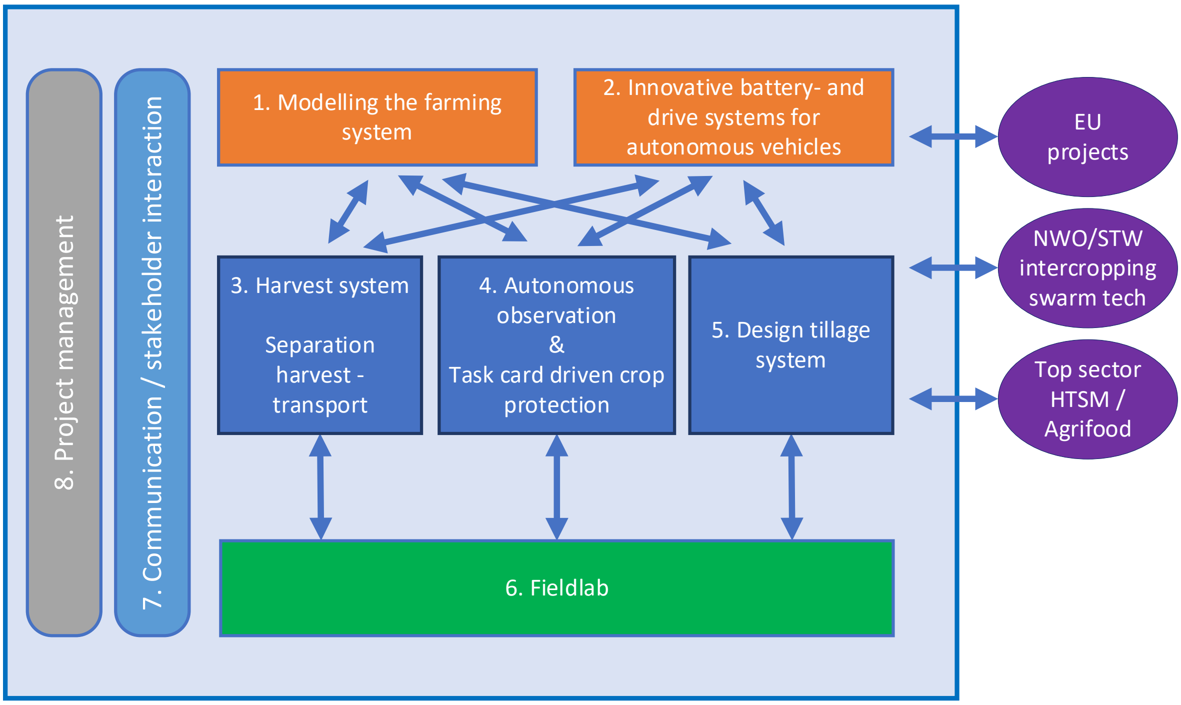



***Figure 2*** *Coherence of work packages in SMARAGD.*

## 1.2 Evaluation of SMARAGD potato harvest strategies

The aim of work package 3 in the SMARAGD project was to develop and test a system design for harvesting big volumes of root crops (like sugar beets or potatoes) with minimal soil compaction. Especially during harvesting, soil compaction is an issue caused by the harvester and the transport of the harvested product in the field. Simulating these processes can help us finding design criteria for the machines based on important performance indicators (Hartmann, 2020).

The main goal of this report was to identify and quantify design parameters for lightweight, autonomous potato harvesting strategies by means of model experiments.

The following research questions were addressed:

1) How do the SMARAGD potato harvest strategies perform compared to conventional potato harvesting methods with respect to required harvesting time?
2) What model input parameters are relevant for achieving the highest harvesting capacity?
3) Are the Smaragd potato harvest strategies economically feasible and how do harvesting costs compare to conventional potato harvesting methods?

In this report the results are presented of simulations of several potato harvesting systems with several variant of conventional harvesting system, CTF variants and some lightweight, autonomous vehicles. The model used for the simulations was developed by Bomers (2017) and Hartmann (2020). This model is referred to as the 'SMARAGD crop operations model'. It is explained in Chapter 3. Firstly, the simulations aimed to get more insight in the total time required for harvesting in the Smaragd concepts compared to conventional methods. Secondly, a sensitivity analysis was done to reveal the input parameters that affected harvest capacity (ha/h) most. With that information a comparison was made between the model outcome and task times as defined in KWIN-AGV (2018). The material & methods are described in chapter 4; the results, discussion and conclusion are described in chapters 4, 5 and 6 respectively.

# 2 Background

In order to compare different mechanisation strategies some common quantitative performance indicators are used, field efficiency, theoretical field time and field capacity.

The Field Efficiency $e_f$ is the ratio between a theoretical field time to the total time spend in the field. The theoretical field time $T_t$ is defined as the time the machine would need to complete an operation in an area equal to the field area when operating at full speed and width on the core operation only. However, during the operation, the machine also spends time on turning, waiting, loading or unloading products, adjustments on implements, manoeuvring, etc. thus forming the total time $T$ of an operation (Hunt and Wilson 2015).

$$e_f = \frac{T_t}{T}$$

Where the theoretical field time is calculated as follows:

$$T_t = \frac{10 \cdot A}{S \cdot w} \text{ [h]}$$

Where $A$ is the actually operated area of the field or the sum of the area of the strips in ha, $S$ is the operation speed in km $h^{-1}$ and $w$ is the operating width of the implement in m. The total operation time is calculated by the discrete event model SMARAGD crop operations. The effective field capacity $C$ is defined as:

$$C = \frac{S \cdot w \cdot e_f}{10} \text{ [ha h}^{-1}\text{]}$$

However, the model output is expressed in both gross and net performance parameters where the gross field area is the total field area including the margin area such as margin strips and traffic lanes. Substituting the expression for the theoretical field time in the equation defining Field Efficiency $e_f$ and substituting $e_f$ in equation defining the effective field capacity results the field capacity as the operated field area $A$ divided by the total operation time $T$:

$$C = \frac{A}{T} \text{ [ha h}^{-1}\text{]}$$

According to the ASABE (2011), for potato harvesting, $C$ should range between 0.31-1.02 ha $h^{-1}$, typically 0.54 ha $h^{-1}$.

The performance of transportation units is assessed by their waiting times and their overall efficiency $e_t$:

$$e_t = \frac{\sum T_{tr,i} - \sum T_{w,i}}{\sum T_{tr,i}} \cdot 100\%$$

where for each transport unit $i$, the operation time $T_{tr,i}$ and waiting time $T_{w,i}$ is computed and summed to totals for all transport units. $e_t$ is separately calculated for both field transport $e_{t,f}$ and road transport units $e_{t,r}$. The specific total time $T_s$ compares between different operations or strategies the sum of the total time spent each unit involved in an operation per unit of area:

$$T_s = \frac{\sum T_i}{A} \text{ [h ha}^{-1}\text{]}$$

As a rough performance indicator for soil compaction, the simulation will sum the mass and calculate the contact pressure index (Stout, 1999) for every axle of every unit for every trafficked spot in the field. Furthermore, the number of passes per spot are counted and the average weight driven in the whole field is calculated. The contact pressure index $CPI$ is defined as the tire load $F_t$ (kN) divided by the vertical tire projection (diameter times width) $d \cdot w$ in $m^2$:

$$CPI = \frac{F_t}{d \cdot w} \text{ [kPa]}$$

It is recommended to keep this value below 25 kPa for soft soils and below 35 kPa for regular soils.

# 3 Crop operations model

The basis for this study was the discrete event model developed by Bomers (2017) and Hartmann (2020), referred to as the ‘SMARAGD crop operations model’. The first objective of this model was simulation of machine movements during harvest of field crops and potato harvesting in particular. Hartmann (2020) continued to develop this model to allow simulation of machine movements on the field for generic field operations. He defined three types of operations. The first type is a mass input operation, where the machine gains weight, for example a harvest operation. The second type is a mass output operation, where the machine loses weight, for example a sowing or fertilizing operation. The third type is a mass neutral operation where the mass of the machine does not change, for example during tillage and weeding. Van ’t Ooster (2019, personal communication) reviewed this model and made it flexible with respect to concept simulation and sensitivity analysis.

The SMARAGD crop operations model communicates with the SMARAGD crop planner module. This crop planner generates a layout of a field consisting of individual strips of crops based on input parameters. It is able to take controlled traffic farming into account and intercropping of different crops.

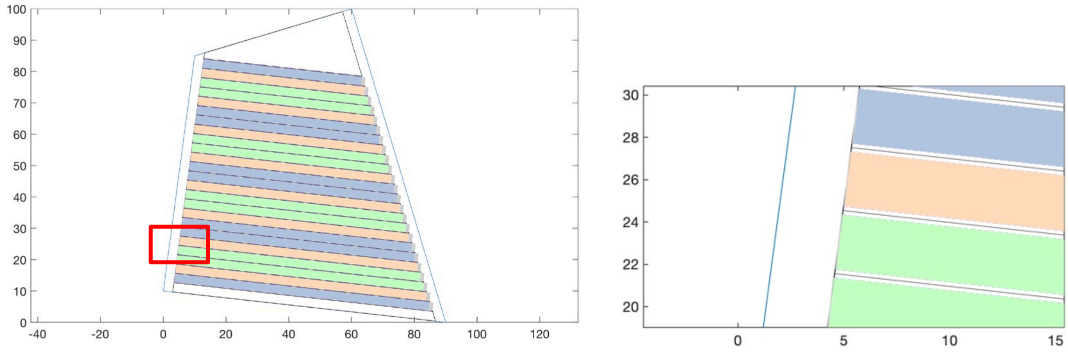



***Figure 3*** *Figure from Hartmann (2020) showing on the left an example of a map layout of a small field with 3 crops in an ABCCBA pattern. Between the strips there is space for the tires of machines to simulate controlled traffic farming, which is shows in the right picture (white).*

Furthermore, the crop planner module is extended with the LINTUL crop growth model (Meuter (2010), Shibu et al. (2010), Wolf (2011&2013)) to simulate the growth of each crop / strip (Zhao (2018), Pereira (2019)). The simulated crop growth is used to generate a schedule of crop operations for all main types of field operations (tillage, seeding, weeding, irrigation, crop protection and harvest). The crop planner module and crop operations model can be used to simulate machine movements throughout the crop season. The movements can be simulated for a monoculture crop or for intercropping and for conventional tracks or controlled traffic farming. Both models are implemented in Matlab 2018b software.

In this report the models are used to simulate all machine movements during a harvest operation of potatoes. This includes a harvester on the field, a few field transport units which transport product on the field to the road and road transport units which transport product from the field to the farm.
Included in the model are processes as transfers of product from the harvester (while driving or on the headland) to transport units, or transfers of product from a field transport unit to a road transport unit.

The required model input with descriptions is given in Appendix 1. The model delivers 42 output parameters, including some parameters to interpret the output (e.g., field size and total yield). 17 parameters are dealing with efficiency and capacity. 18 parameters are soil indicators, just giving a simple guidance to soil compaction by means of the contact pressure index. For all output parameters and their descriptions, see Appendix 2.

# 4 Materials and methods

The focus of this report is a model-based analysis to compare lightweight potato harvest strategies (SMARAGD) with current state-of-art harvesting methods of potatoes in a monoculture potato field. For all alternatives, the machine movements for the potato harvest operation were simulated for a rectangular field.

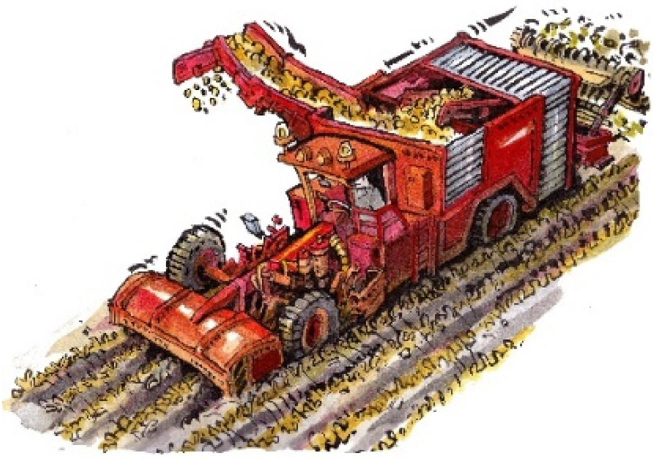
In this research, the model experiments and system evaluations were done in an iterative way. As a start the 'SMARAGD crop operations' model was simulated with default inputs of each concept. In the first set of simulations, the harvester efficiency in the Smaragd concepts was quite low due to long waiting times for the harvester. For that reason, a sensitivity analysis was done to find out how a selected set of input parameters influenced the harvester efficiency. Ideally the harvester waiting time would be zero, to ensure a continuing harvest process. In that case the harvester can maximize the field area harvested during workable days (highest Field efficiency). The sensitivity analysis for these output parameters was done for most concepts. After completing the simulations, the economic results were evaluated for all concepts considered.

## 4.1 Concepts

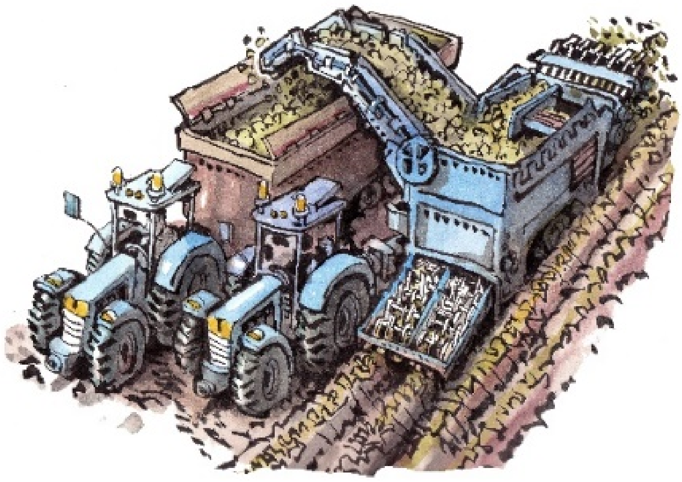
The chosen start and endpoint of the simulated harvesting process is to start with all units at the gate of the field and delivery of the harvested potatoes at the farm and storage in crates. A standard 6 ha potato field with length 300 m and width 200 m, located at a distance of 1 km from the farm was simulated for all concepts.

In this report, 8 concepts were evaluated. The concepts 1 to 4 are more or less conventional. The concepts 5 to 8 are Smaragd-concepts using a lightweight autonomous agricultural platform like the AgroIntelli Robotti equipped with a trailed potato crate harvester. The harvester system concepts were defined as:

1. Conventional 3m – 4 rows:
   A conventional self-propelled potato harvester which harvests 4 rows at once in a working width of 3 meter. The harvester has an internal buffer and unloads in a tipper beside while driving. The tractor with tipper performs both the field and road transport. Controlled Traffic Farming (CTF) is not applied.

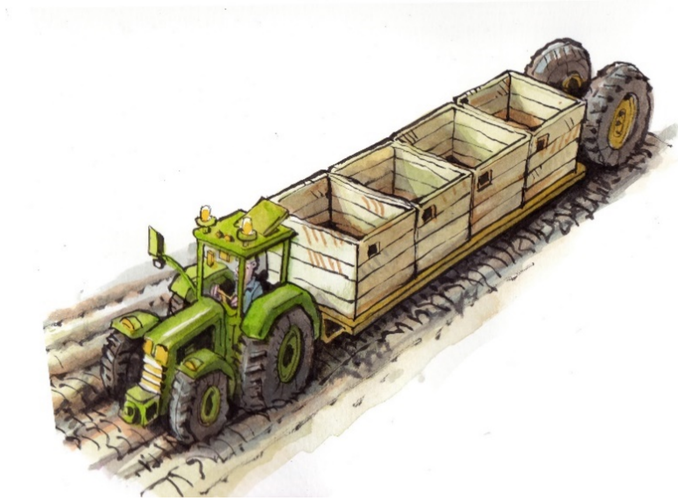


2. Conventional – 1.5 m – 2 rows:
   A conventional trailed bunker potato harvester which harvests 2 rows at once in a working width of 1.5 meter. The harvester unloads in a tipper beside while driving. The tractor with tipper performs both the field and road transport. CTF is not applied.

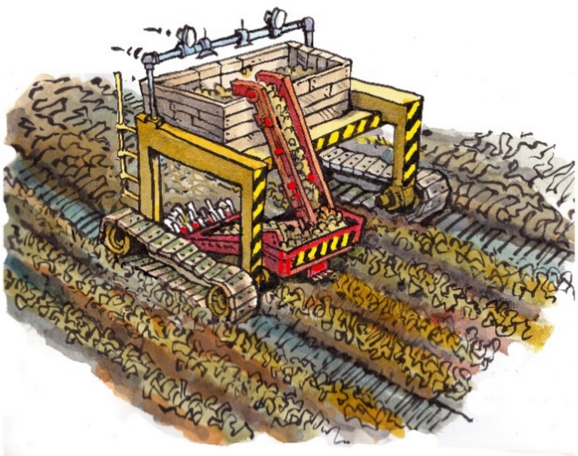


3. Conventional – 1.5 m – 2 rows - CTF:
   As #2, only with CTF and only unloading in a tipper at the headland.

4. CTF - 2 rows trailed harvester, one crate:
   A trailed potato harvester which harvests 2 rows at once in a working width of 1.5 meter. The harvester unloads in 6-8 crates on a trailer alongside while driving. CTF is applied for both the harvester and the tractor with trailer. The tractor with trailer performs both the field and road transport. In this concept the harvester is provided with one crate as a small buffer. The model requires a small buffer for a reliable outcome, in this case one crate.



5. Smaragd – one-row harvester – 100 kg buffer:
   One, one-row autonomous harvester operates within CTF; the harvester unloads while driving in one or two crates on a dedicated field transport unit. The field transport unit picks up the full crates behind the harvester from the same strip. Field transport units unloads full crates at the headland automatically to the road transport which is a tractor with conventional trailer as in concept 4. The road transport unit is used to transport the full crates to the farm.
6. Smaragd – one-row harvester – 500 kg buffer:
   As #5, only with a 500 kg buffer instead of 100 kg buffer.
7. Smaragd – two-row harvester – 100 kg buffer:
   As #5, only harvesting 2 potato rows at once instead of one.



8. Smaragd – two-row harvester – 500 kg buffer:
   As #6, only harvesting 2 rows at once instead of one.

Four variants were chosen for the Smaragd concepts: a one-row and a two-row harvester with a buffer capacity of 100 or 500 kg. A two-row harvester is expected to harvest more potatoes per unit of time, to fill the buffer is faster as a consequence, and to need the transport unit sooner. A one-row harvester as well as the transport units are expected to have on average a lower weight since machine weight is less than that of a two-row harvester and a lower percentage of their buffer capacity is needed, but at the same time both machines pass more frequent on the same tracks. This may have benefits with respect to soil compaction. Since only one transport unit can pass a lane, the harvester will have more waiting time in the case the harvester has no buffer or only a small buffer capacity. That is why also a higher buffer capacity was chosen.

The chosen default model input parameter values for the 'Available tech' concepts (1-4) are given in Appendix 3. The default model input parameter values for the Smaragd concepts 5 to 8 are given in Appendix 4.

## 4.2 Sensitivity analysis

In the simulation results with the default settings, the effective field capacity of the harvester in the Smaragd concepts was quite low due to long waiting times for the harvester. For that reason, a sensitivity analysis was done to find how a selected set of input parameters influenced the harvester efficiency. Ideally the harvester waiting time would be zero, to ensure a continuing harvest process. The sensitivity analysis has been done for all concepts, except concepts 5 and 7 (Smaragd with a 100 kg buffer capacity). The focus was on the output parameters Field Efficiency and Total Wait Time for the harvester.

The next 4 input parameters were selected within the sensitivity analysis with motivation:

- Buffer capacity [kg]: a bigger buffer capacity at the harvester is expected to lower the Machine Wait time for the harvester.
- Buffer Threshold [%]: with a lower Buffer Threshold at the harvester, the harvester is expected to have to wait less for the transport unit.
- Nr. of units [-]: what is the minimum number of transport units needed for a low harvester waiting time since transport units should not be bottleneck in the harvesting process.

- Transport Capacity [kg]: a higher Transport Capacity is expected to lower the harvester waiting time.

First, some effects have been tested manually; then an automatic sensitivity analysis was performed with a certain range and fixed step sizes. The chosen variables per input parameter per (group of) concept are given in Table 1 to Table 3.

***Table 1*** *Variables for input parameters in concept 1 – 3 for the sensitivity analysis.*

| Parameter | range | Step size | default (concept) |
|---|---|---|---|
| Buffer capacity (kg) | 2000 - 12000 | 2000 | 8000 (1)<br>6000 (2,3) |
| Buffer threshold (%) | 5 - 95 | 10 | 80 |
| Transport capacity (kg) | 8000 - 33000 | 5000 | 18000 |
| Number of transport units | 1 - 5 | 1 | 2 |

***Table 2*** *Variables for input parameters in concept 4 for the sensitivity analysis*.

| Parameter | range | Step size | default |
|---|---|---|---|
| Buffer capacity (kg) | 1200 - 9600 | 1200 | 1200 |
| Buffer threshold (%) | 5 - 95 | 10 | 80 |
| Transport capacity (kg) | 7200 - 12000 | 1200 | 7200 |
| Number of transport units | 1 - 5 | 1 | 3 |

***Table 3*** *Variables for input parameters in Smaragd concepts 5 to 8 for the sensitivity analysis.*

| Parameter | range | Step size | default (concept) |
|---|---|---|---|
| Buffer capacity (kg) | 200 - 1200 | 200 | 100 (5, 7)<br>500 (6, 8) |
| Buffer threshold (%) | 5 - 95 | 10 | 80 |
| Transport capacity (kg) | 1200 - 3600 | 1200 | 1200 |
| Number of transport units | 1 - 5 | 1 | 5 |

## 4.3 Optimising concepts with stacking effects

The manual one-at-a-time sensitivity analysis showed that the tested input parameters have an effect on the simulation results, so there are possibilities for optimising the concepts. For this reason, the effect has been explored of changing several input parameters simultaneously. For each of the 4 selected input parameters (Buffer capacity, Buffer threshold, Transport capacity and Number of transport units) the most efficient value was selected based on highest Field Efficiency and lowest Total wait time of the harvester.

This manual optimisation has been done only for the concepts 1 (Conventional 3m – 4 rows), 6 and 8 (Smaragd, one respectively two-row harvester, 500 kg buffer capacity). The calculated combinations of simultaneously changed input parameters are given in Table 3. From the simulation results the output parameters Field Efficiency, Total wait time harvester and Gross effective field capacity are evaluated. The results do not pretend to present overall optimum settings for input parameters.

***Table 4*** *Tested default and optimised input parameters as stacking effect in concepts 1, 6 and 8.*

| | Concept 1 | | Concept 6 and 8 | |
|---|---|---|---|---|
| Parameter | default | optimised | default | optimised |
| Buffer capacity (kg) | 8000 | 12000 or 15000 | 500 | 1200 |
| Buffer Threshold (%) | 80 | 5 | 80 | 10 |
| Transport capacity (kg) | 18000 | 23000 or 28000 | 1200 | 2400 |
| Number of transport units | 2 | 2 | 5 | 2 |

For the manually optimised concepts also the use of the transport units was evaluated as well as contact pressure index $CPI$ of a rough indication of surface soil loads. The performance indicators evaluated for the transport units were overall efficiency for field and road transport ($e_{t,f}$ and $e_{t,r}$), total waiting time ($\sum T_{w,i}$) and for the mechanisation as a whole specific total time ($T_s$ in h ha$^{-1}$). The definition of these performance indicators is given in Chapter 2.

## 4.4 Economical evaluation

Based on the outcome of the Matlab simulations the economic results of the concepts were evaluated. The following economic comparison was used. The concepts for potato harvest were divided into five different methods:

1. Self-propelled harvester with 3 meters operating width
2. Trailed bunker harvester with 1.5-meter operating width (no CTF)
3. Trailed bunker harvester with 1.5-meter operating width (CTF)
4. Trailed harvester with 1.5-meter operating width (CTF)

Autonomous harvester variants, which are:

5. 1-row harvester with 100 kg buffer
6. 1-row harvester with 500 kg buffer
7. 2-row harvester with 100 kg buffer
8. 2-row harvester with 500 kg buffer

The costs of the field activity were split into three parts, mechanisation, labour and energy costs. Per method/variant the cost per hectare were calculated. The Matlab model used a 6-hectare field size as starting point. The simulation results present the time needed for the activity. The activity ends when the potatoes are delivered at the barnyard and stored in crates. For methods 1 to 3 this means an additional handling equipment is needed (hopper, conveyors and box fillers). For the autonomous harvester variants, an additional tractor with trailer is added to realize the road transport.

*Mechanisation costs*
The mechanisation costs are derived from the KWIN-AGV 2018. The given replacement costs, year costs and average utilization are used to calculate the activity price per machine/equipment used. With multiple machines the costs per machine are summed.

$$\text{Activity price } = \frac{\text{Average Replacement value} \cdot (\text{year costs} + 1\%)}{\text{Utilization (in ha or in hours)}}$$

The activity price is calculated per hectare or per hour, depending on the utilization stated in the KWIN-AGV 2018 (quantitative information arable and vegetable farming). With a utilization stated in hours, the time for the activity was used. With a utilization stated in hectares, the field size was used as reference.

*Labour costs*
The labour costs are calculated based on the total operation time $T$ given by the model. Based on expert judgement an estimate was made on the number of persons $P$ needed. The hourly wages $W_h$ are based on the CLA of arable farming in the Netherlands. An hourly wage of EUR 20,- is used.

$$Labour\ costs\ = T \cdot P \cdot W_h$$

*Energy costs*
The power of the mechanisation used is taken as reference to calculate the energy consumption. This is based on the calculation methods used by the KWIN-AGV (2018). The energy consumption is calculated per hour and multiplied by the hours needed for the activity. This is done per tractor or self-propelled harvester. The energy carrier used in all methods is diesel. The reference price of diesel is taken form the KWIN-AGV (2018) and is EUR 1.10 per liter.

**Starting point mechanisation and labour per harvest method/concept.**

1. Conventional 3m – 4 rows:
   - 1x Self-propelled bunker harvester, 4-row, 3 meters operating width
   - 3x Tractor (70-80 kW)
   - 3x Tipping trailer (18 ton, hydraulic, tandem)
   - 3x All-round employees (employees driving 3 tipping trailers)
2. Conventional – 1.5 m – 2 rows:
   - 1x Tractor (80-100 kW)
   - 1x Trailed bunker harvester, 2-row, 1.5-meter
   - 2x Tractor (70-80 kW)
   - 2x Tipping trailer (18 ton, hydraulic, tandem)
   - 3x All-round employees
3. Conventional – 1.5 m – 2 rows - CTF:
   - 1x Tractor (80-100 kW)
   - 1x Trailed bunker harvester, 2-row, 1.5-meter
   - 2x Tractor (70-80 kW)
   - 2x Tipping trailer (18 ton, hydraulic, tandem)
   - 3x All-round employees
4. CTF - 2 rows trailed harvester, one crate:
   - 1x Tractor (80-100 kW)
   - 1x Trailed harvester, 2-row, 1.5-meter
   - 2x Tractor (70-80 kW)
   - 2x Crate trailer, 8 crates
   - 3x All-round employees
5. and 6. Smaragd – one-row harvester – 100 kg (#5) and 500 (#6) kg buffer:
   - 3x Autonomous harvester, 75 kW
   - 1x Harvester, simple, 1-row
   - 2x Lifting mast, 2000 kg
   - 1x Tractor (70-80 kW)
   - 1x 3-axle dog trailer (25 tons)
   - 2x All-round employees (one for transport, one supervisor)
7. and 8. Smaragd – two-row harvester – 100 kg (#7) and 500 (#8) kg buffer:
   - 3x Autonomous harvester, 75 kW
   - 1x Harvester, simple, 2-row
   - 2x Lifting mast, 2000 kg
   - 1x Tractor (70-80 kW)
   - 1x 3-axle dog trailer (25 tons)
   - 2x All-round employees (one for transport, one supervisor)

# 5 Results

This chapters presents the results of model experiments with the SMARAGD crop operations model. Section 5.1 present the results based on the default settings of the input parameters per system concept as defined in Appendix 3 and 4. Section 5.2 presents the results of the sensitivity analysis. In section 5.3 the results of simultaneous parameter adaptation are given. In section 5.4 presents the results of the economic evaluation and in section 5.5 the total operation times computed by the model are compared to operation times based on tasks times in KWIN-AGV 2018.

## 5.1 Results default settings

Figure 4 shows four results of the model outcome with the default input in concept 4. In the case of the initial concept 4 (4A), the trailed harvester had a very long waiting time due to an inefficient transport regarding CTF (only one machine per lane). For that reason, in concept 4B a buffer capacity of one crate (1200 kg) is added, which sharply reduced the total operation time by reducing total wait time for both the harvester and the transport units.

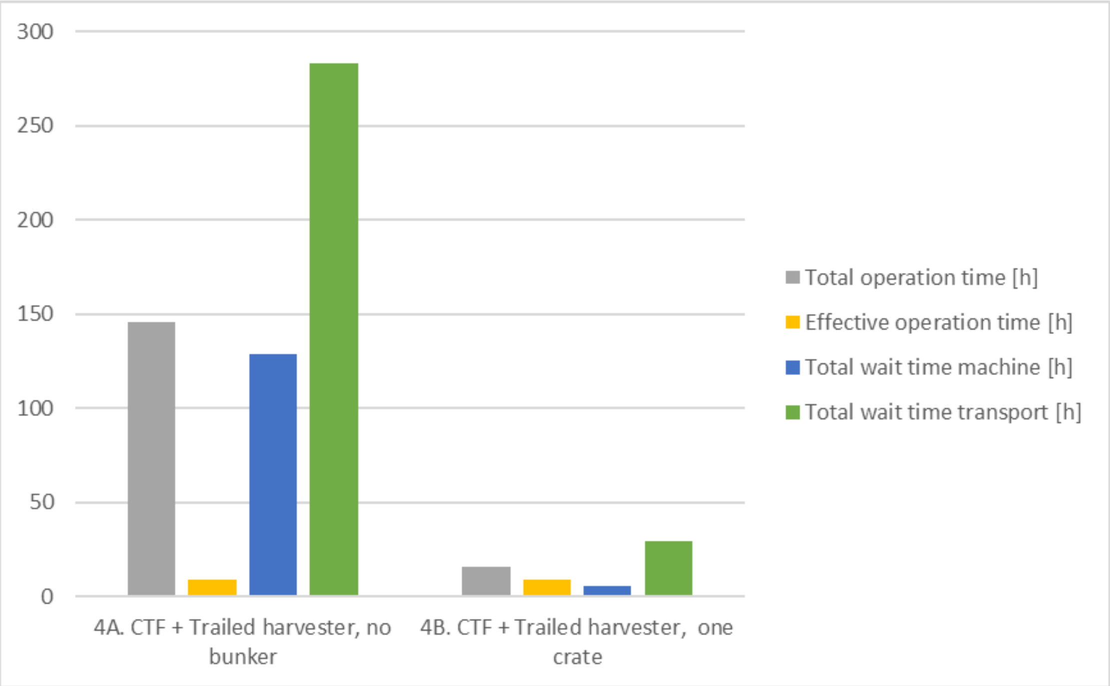



***Figure 4*** *Effect of adding a small buffer capacity of 1200 kg in concept 4 on Total operation time, Effective operation time, Total wait time machine (=harvester) and Total wait time transport.*

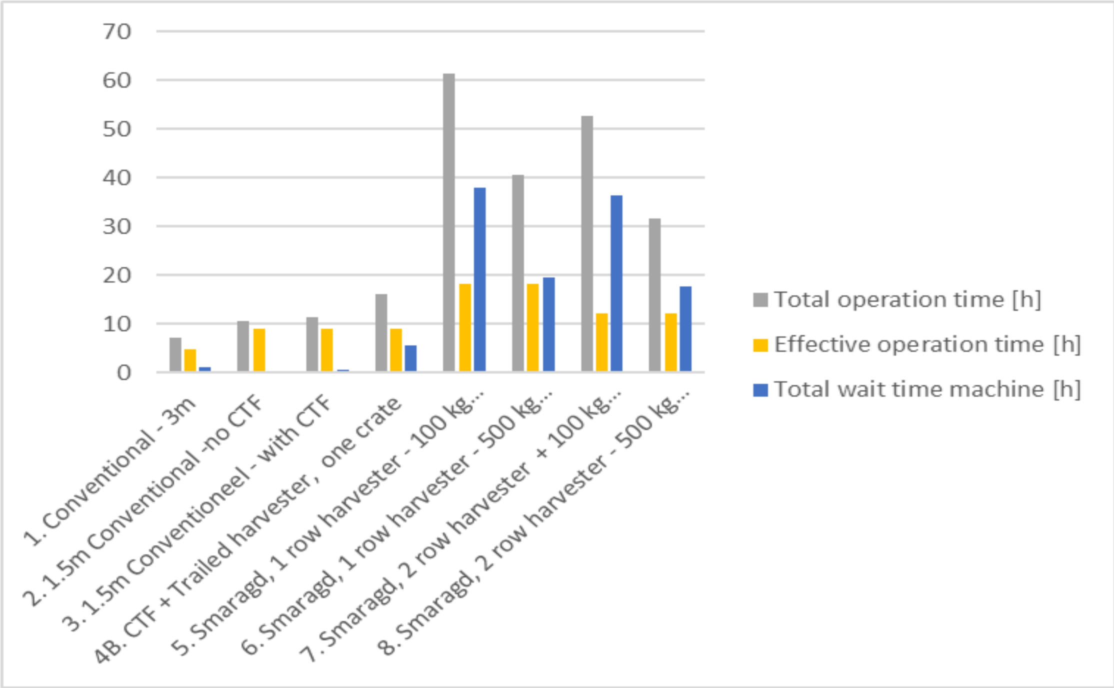



***Figure 5*** *Comparison of time required for the potato harvester in 8 concepts.*

In general, all conventional concepts (1-3, 4B) have a lower Total and Effective operation time, compared with the Smaragd concept's (5 – 8) and low wait time for the harvester (Total wait time machine) (Figure 5). Especially concept 1 *conventional self-propelled 4 rows potato harvester* has the lowest Total and Effective operation time. The Smaragd concept 5 needs until 8 times longer Total operation time and about 4 times longer effective operation time.

In all Smaragd concepts the Total operation time of the harvester is remarkably longer than the Effective operation time. In these concepts an inefficient field transport (only one transport unit per lane) gives long waiting times for the transport units and also a long waiting time for the harvester and thus a long Total operation time. Also, the Smaragd one-row harvesters (5 and 6) need more Effective operation time than the Smaragd two-row harvesters (7 and 8), because the one-row harvester has to pass each lane twice to harvest both rows. A higher buffer capacity (500 kg vs 100 kg) in the Smaragd concepts, both 1 and 2 rows harvesters, leads to lower Total operation time, because of a strongly decreased Waiting time for the harvester; per lane only one transport unit can pass.

## 5.2 Sensitivity analysis

The model outcome with default input parameters (best guess of experts) showed long waiting times for the harvester in the Smaragd concepts. The result of the sensitivity analysis for the selected input parameters are presented in this section with focus on the Smaragd concepts. The field efficiency and waiting time of the harvester were the performance indicators examined. Ideally, the waiting time would be zero to ensure a continuous harvest process.

### 5.2.1 Concepts

Figure 5 shows the results for the sensitivity analysis in concept 1 – 3 for 4 parameters, namely Buffer Capacity, Buffer Threshold, Transport Capacity and number of transport units. The concept Conventional 3 m has overall a lower Field Efficiency and a higher Total Waiting time for the harvester, compared with the Conventional 1.5 m concepts. A higher buffer capacity with match transport capacity increases field efficiency to beyond the range investigated. The optimum buffer threshold for given nominal values is approximately 45%.

The concepts 2 and 3 (Conventional 1.5 m with or without CTF) are quite comparable in the model results. The higher the buffer capacity for the harvester, the higher is the Field efficiency and the lower the Total wait time for the harvester. A buffer capacity more than 8000 kg hardly increases the Field efficiency and hardly decreases Total wait time which is close to zero already. For Buffer threshold, the optimum for given nominal values is between 65% and 75%. A lower buffer threshold does not increase the Field Efficiency. A transport capacity higher than 8000 kg does not lead to much higher Field efficiency. Decreasing the number of transport units from 2 to 1 result in a sharply increasing Total waiting time for the harvester and thus a decreasing Field efficiency.

More than 2 transport units has no effect for any of the 3 conventional concepts.

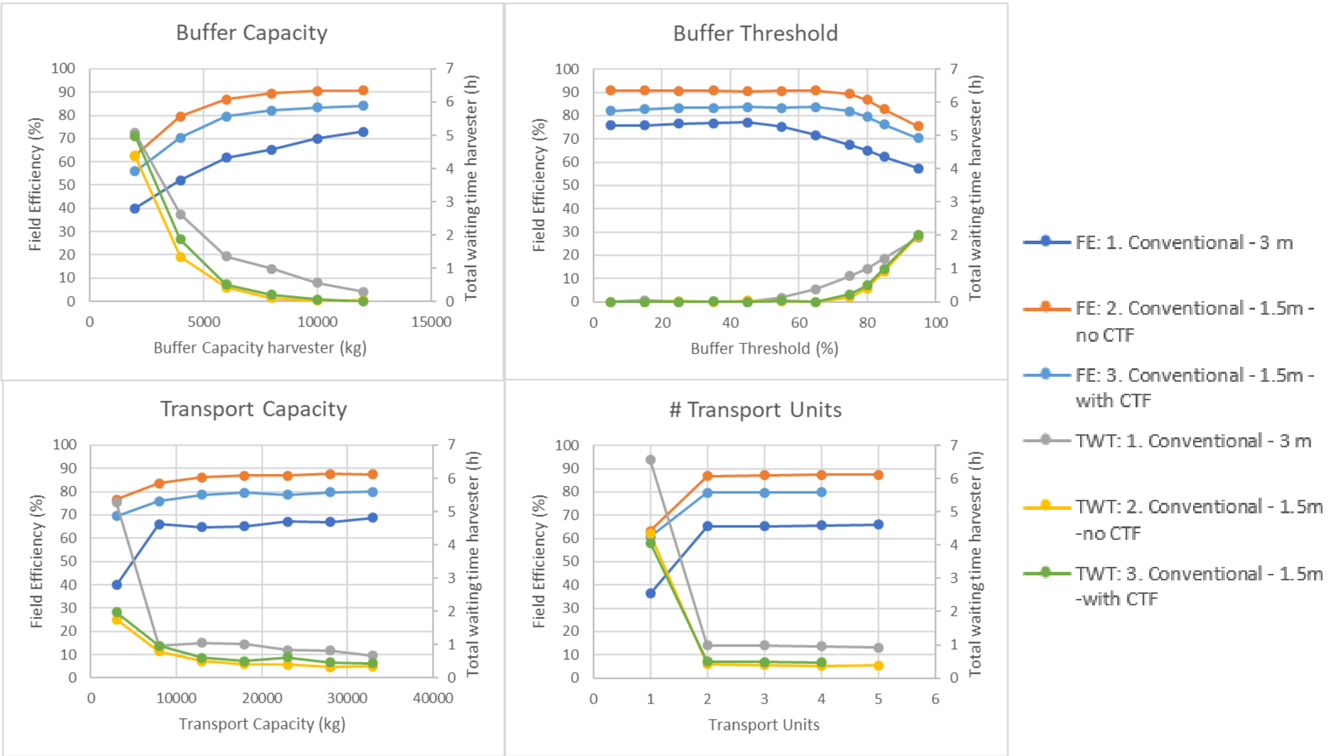



***Figure 6*** *Sensitivity analysis for the parameters Buffer Capacity, Buffer Threshold, Transport Capacity and number of transport units in 3 conventional concepts (1-3). FE: Field Efficiency, TWT: Total waiting time for the harvester.*

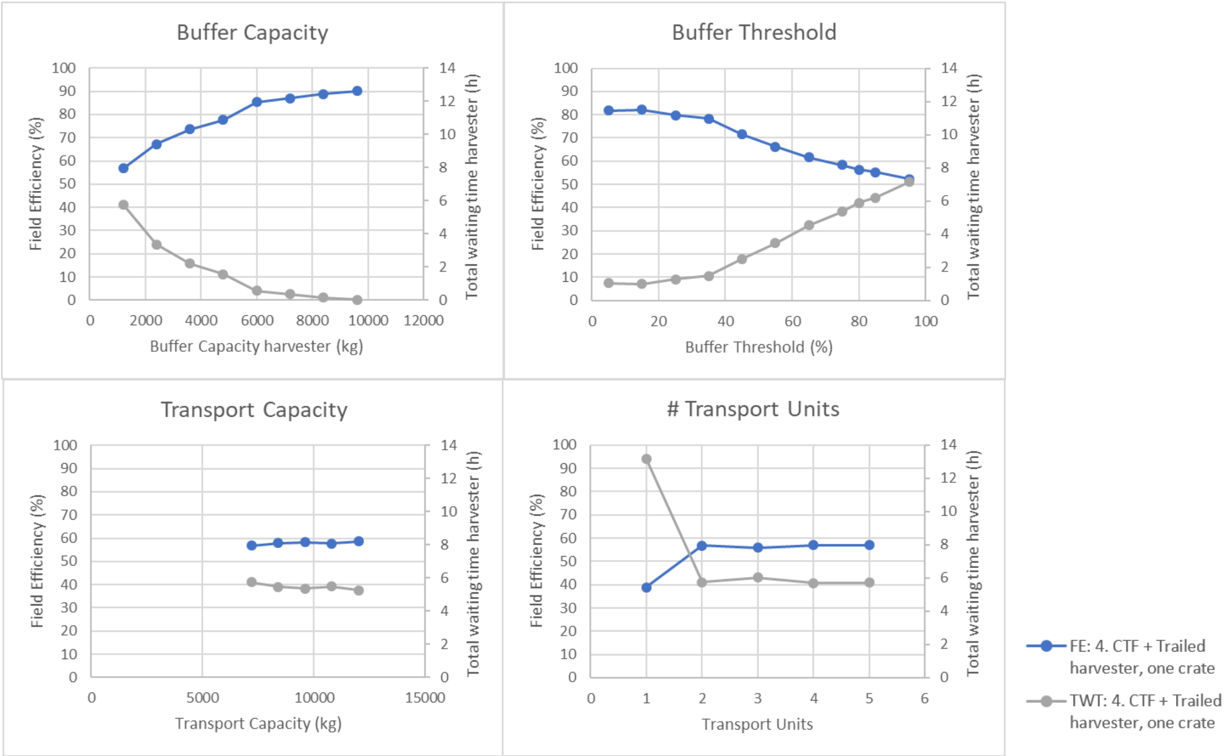



***Figure 7*** *Sensitivity analysis for the parameters Buffer Capacity, Buffer Threshold, Transport Capacity and number of transport units in the conventional concept 4 (Trailed harvester with CTF). FE: Field Efficiency, TWT: Total waiting time for the harvester.*

Figure 7 shows the graphs for the concept with the trailed two-row harvester with CTF. The chosen value for the buffer capacity in this concept was 1200 kg (one crate). An increasing buffer capacity results in a higher Field efficiency and a lower Total wait time. A lower Buffer threshold (was 80%) also leads to a higher Field efficiency with an optimum around 35%. Changing the transport capacity in the given range 7200 to 12000 kg with nominal buffer capacity of 1200 kg on the harvester doesn't influence the Field efficiency neither the Total wait time.

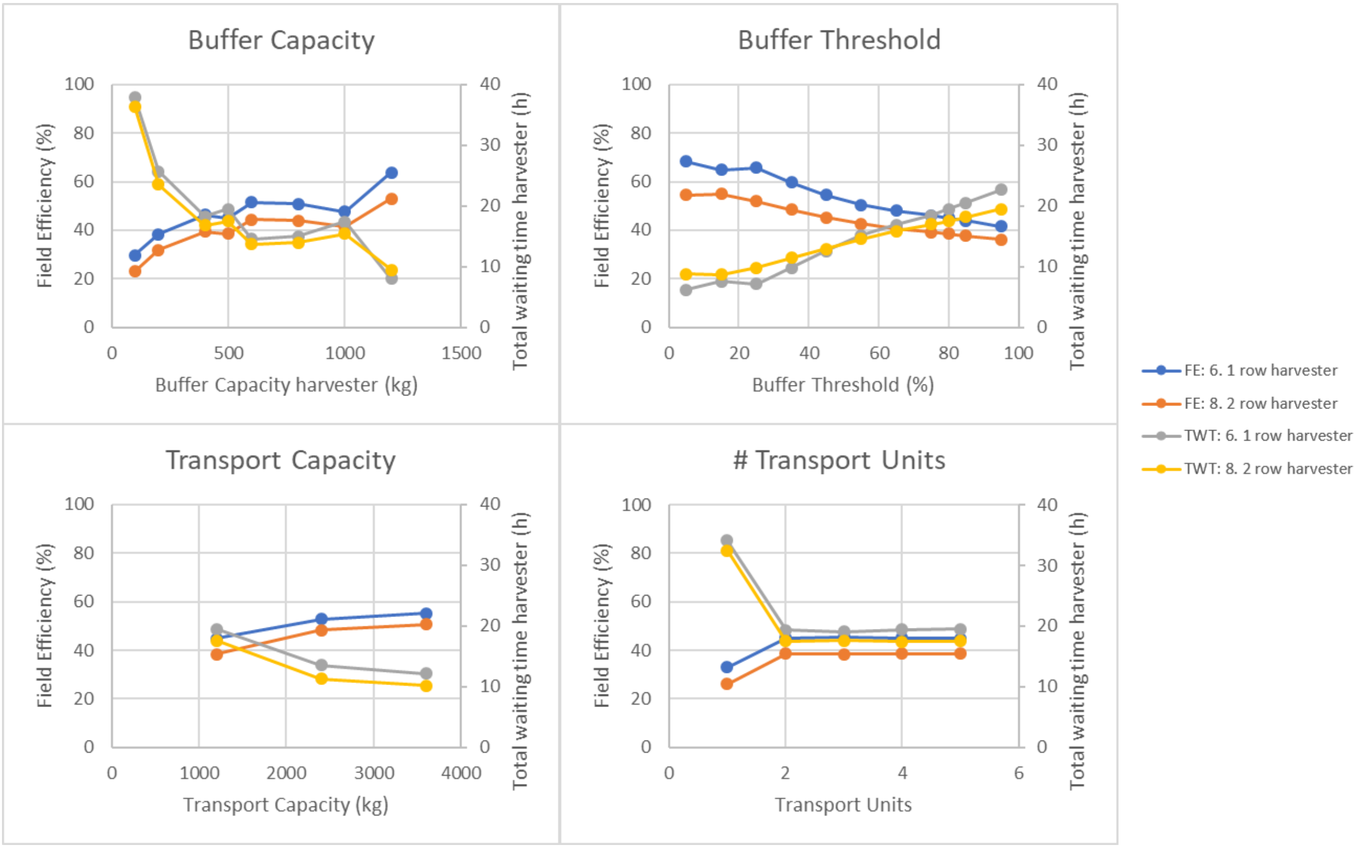



***Figure 8*** *Sensitivity analysis for the parameters Buffer Capacity, Buffer Threshold, Transport Capacity and number of transport units in the Smaragd concepts 6 and 8. FE: Field Efficiency, TWT: Total waiting time for the harvester.*

According to Figure 8 the Field Efficiency increases with an increasing Buffer capacity. Note that concept 6 and 8 in a Buffer Capacity of 100 kg are the concepts 5 and 7, respectively. The maximum buffer capacity in this analysis was 1200 kg (one crate), which has also the lowest Total waiting time, which is however not reduced to zero. A lower Buffer threshold results also in a lower Total waiting time until a Buffer threshold of around 20%. A higher Transport capacity of 2 or 3 crate of 1200 kg each does not improve the Field efficiency much. Using two Transport units in this concept is optimal. Increasing this number does not improve the Field Efficiency nor Total waiting time, but lowering to just 1 transport unit results in a much lower Field efficiency and higher waiting time for the harvester.

### 5.2.2 Relevancy of input Parameters

In general, the input parameters Buffer capacity and Buffer threshold show the biggest effects on the Field efficiency and the Total waiting time for the harvester for all concepts. Increasing the Buffer capacity or decreasing the Buffer threshold results in a higher Field Efficiency. However, lowering the Buffer threshold below 35-45% in conventional concept 1 and 4 and below 65% for concepts 2 and 3 does not improve the Field Efficiency, but it does in the Smaragd concepts where the optimum is around 20%.

For most concepts the Transport capacity and number of Transport units doesn't influence much the Field Efficiency neither the Total waiting time for the harvester. In the 3 conventional concepts (1-3) there is a critical minimum for the Transport capacity for concept one which equals the buffer capacity of the harvester but is quite lower than common in practice (about 8000 kg). In the Smaragd concepts the Field Efficiency is more sensitive for the Transport capacity.

In all concepts there was no effect on Field Efficiency of increasing the number of transport units from 2 until 5, but lowering the number of transport units from 2 to 1, increases the Total waiting time of the harvester and thus decreases the Field Efficiency of the harvester.

## 5.3 Optimising concepts by stacking effect

In Figure 9 to Figure 11 the effects are presented for the effects of simultaneous change of several input parameters in the concepts 1, 6 and 8. The conventional concept 1 *3-meter harvester - 4 rows* with default input was already quite optimal. The field efficiency and the gross effective field capacity hardly increase with increased Buffer capacity and Transport Capacity and a decreasing Buffer threshold (Figure 8). The total wait time for the harvester can be reduced until zero by stacking an increasing Buffer capacity, Transport Capacity and a decreasing Buffer threshold with selected values shown in Table 6. It is expected that an increasing Buffer Capacity and Transport Capacity also will cause more soil compaction in the field.

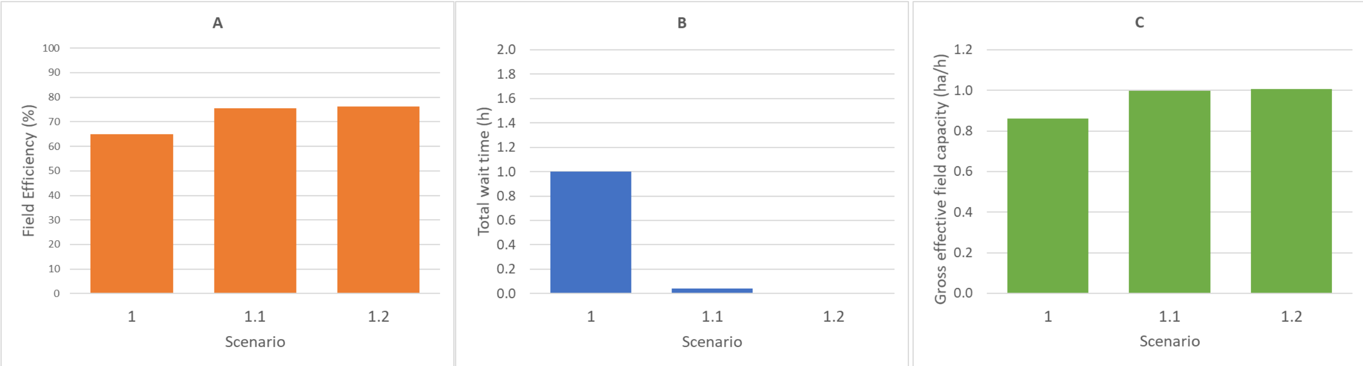



***Figure 9*** *Stacking effect of optimising input parameters on Field Efficiency (A), Total wait time harvester (B) and Gross effective field capacity (C) in variants of concept 1 (Conventional – 3m – 4 row).*

***Table 6*** *Selected parameter values used in stacking optimising input parameters for concept 1 (Conventional – 3m – 4 row).*

| Concept | Buffer size on harvester [kg] | Buffer threshold [%] | Buffer size transport unit [kg] |
|---|---|---|---|
| 1 (default) | 8000 | 80 | 18000 |
| 1.1 | 12000 | 5 | 18000 |
| 1.2 | 12000 | 5 | 23000 |

In concepts 6 and 8, the stacking of optimized input parameters ensures a much higher Field efficiency and gross effective field capacity and a shorter total wait time for the harvester (Figure 10 and Figure 11). The effects of the selected optimised parameters are comparable for both concept 6 and 8. Values for the selected optimised parameters are given in Table 6 and Table 7. The decreased number of Transport units from 5 (default) to 2 transport units does not influence the Field efficiency, total wait time of the harvester and the gross effective field capacity, as already shown in Figure 8, but is expected to have a positive impact on the economical evaluation. The decreased buffer threshold and the increased buffer size have a big positive effect on all three performance indicators. Doubling the capacity of a transport unit from one to two crates has an additional small effect.

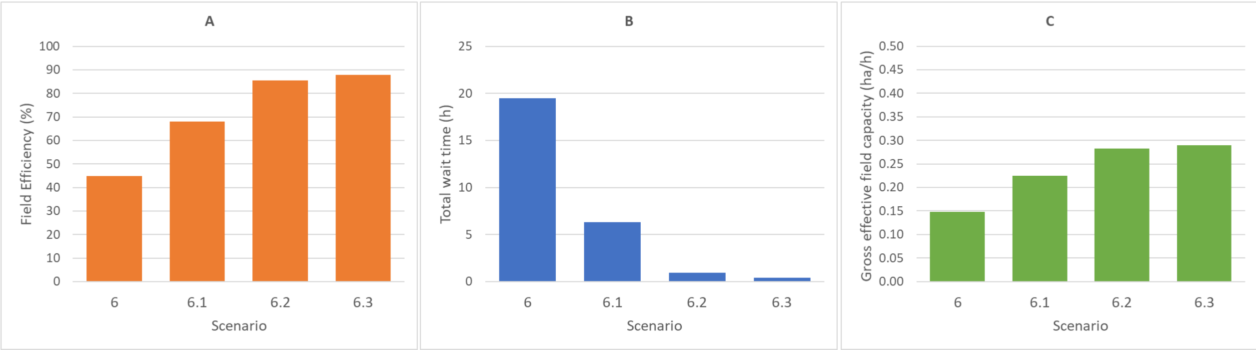



***Figure 10*** *Stacking effect of optimising input parameters on Field Efficiency (A), Total wait time harvester (B) and Gross effective field capacity (C) in variants of concept 6 (Smaragd - one-row harvester).*

***Table 7*** Selected parameter values used in stacking optimising input parameters for concept 6 (Smaragd – one-row harvester).

| Concept | Buffer size on harvester [kg] | Buffer threshold [%] | Buffer size transport unit [kg] | Nr of transport units [-] |
|---|---|---|---|---|
| 6 (default) | 500 | 80 | 1200 | 5 |
| 6.1 | 500 | 10 | 1200 | 2 |
| 6.2 | 1200 | 10 | 1200 | 2 |
| 6.3 | 1200 | 10 | 2400 | 2 |

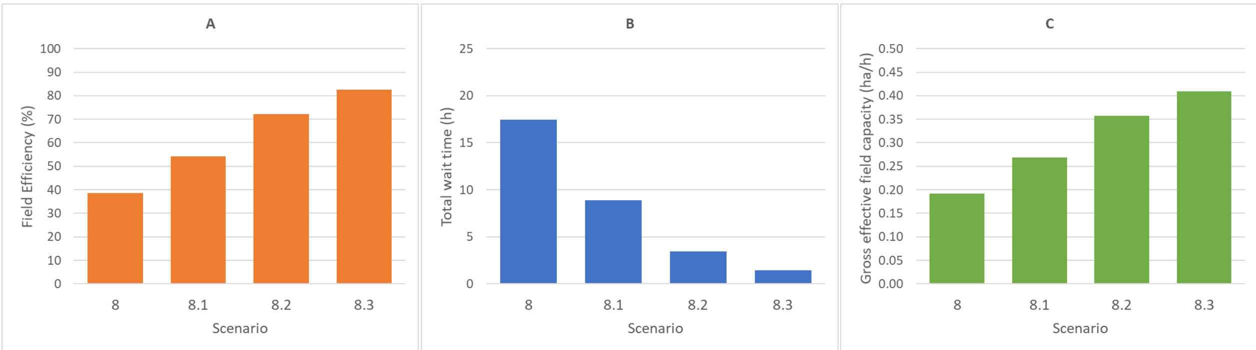



***Figure 11*** *Stacking effect of optimising input parameters on Field Efficiency (A), Total wait time harvester (B) and Gross effective field capacity (C) in variants of concept 8 (Smaragd - two-row harvester).*

***Table 8*** Selected parameter values used in stacking optimising input parameters for concept 8 (Smaragd – two-row harvester).

| Concept | Buffer size on harvester [kg] | Buffer threshold [%] | Buffer size transport unit [kg] | Nr of transport units [-] |
|---|---|---|---|---|
| 8 (default) | 500 | 80 | 1200 | 5 |
| 8.1 | 500 | 10 | 1200 | 2 |
| 8.2 | 1200 | 10 | 1200 | 2 |
| 8.3 | 1200 | 10 | 2400 | 2 |

The highest field efficiency and gross effective field capacity are achieved with a stack of all 4 optimized input parameters, namely Buffer Threshold, Transport Units, Buffer Capacity and Transport Capacity (Table 8). The total wait time of the harvester can be reduced to 1.4 and 0.4 hours for the concepts 8 and 6, respectively. Thus, resulting in a gross effective field capacity of 0.41 and 0.29 hectare per hour in respectively the concepts 8 and 6. In comparison, the self-propelled 4 row harvester (concept 1) achieves a maximum gross effective field capacity of 1.01 hectare per hour (Figure 12).

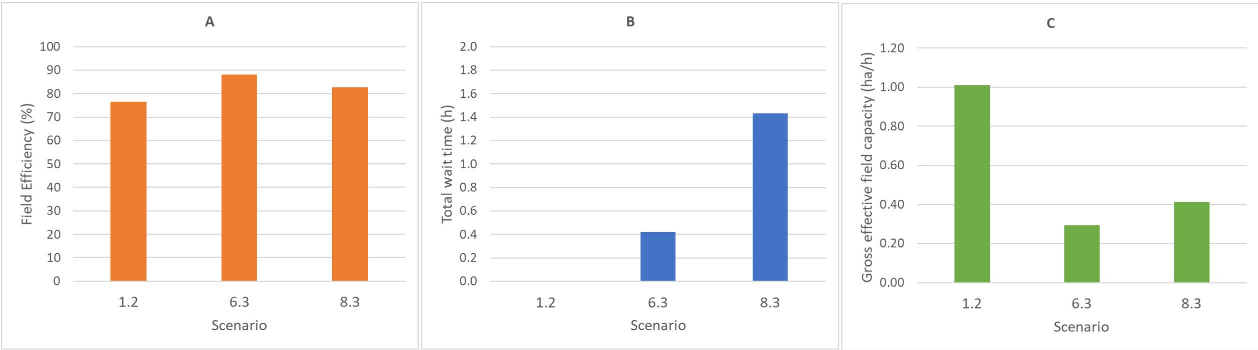



***Figure 12*** *Performance of 3 optimised concepts for the input parameters Field Efficiency (A), Total wait time harvester (B) and Gross effective field capacity (C).*

**Table 9** *Manually optimised parameter values used in 3 optimised concepts (1, 6 and 8).*

| Concept | Description | Buffer size on harvester [kg] | Buffer threshold [%] | Buffer size transport unit [kg] | Nr of transport units |
|---|---|---|---|---|---|
| 1.2 | Conventional 4-row self-propelled bunker harvester | 12000 | 5 | 23000 | 2 |
| 6.3 | Smaragd 1-row harvester | 1200 | 10 | 2400 | 2 |
| 8.3 | Smaragd 2-row harvester | 1200 | 10 | 2400 | 2 |

After evaluating the performance of the harvester also for the manually optimised concepts, the performance of the transport units was analysed as well as the contact pressure index with underlying parameters. The transport and contact pressure related results are depicted in Table 9. Field transport is done with autonomous transport units. The efficiency of field transport is with 63% smallest in the concept with the 1-row autonomous harvesters. Partly this is caused by increased waiting time partly as a result of separate field and road transport. The efficiency with the 2-row autonomous harvester is in between the 4-row conventional harvester and the 1-row autonomous harvester. Road transport efficiency was low in the Smaragd concepts 6.3 and 8.3 since the same amount of product (242 tonnes) had to be transported in a long total operation time of 6.0, 20.7 and 14.8 hours of concepts 1.2, 6.3 and 9.3 respectively. Total number of filled field and road transports and total wait time are indicated in Table 9. For the conventional 4-row harvester (1.2) this was zero, because road transport was done by field transport units.

The lower part of Table 9 gives indicators for soil loads and contact pressure indices. It is clear that in CTF the percentage of the field used for traffic is much lower, 77.9% for concept 1.2 vs 9.5% for concepts 6.3 and 8.3. The average number of tire passages is much higher for the Smaragd concepts 6.3 and 8.3 though the field location with most tire passages does not differ much with 41, 50 and 32 for concepts 1.2, 6.3 and 8.3 respectively. The average total weight per track indicates the total weight of all passages average of the area of all tracks. This is with 35.8 and 23.2 tonnes higher for the Smaragd concepts 6.3 and 8.3 respectively than the 17.1 tonnes for the Conventional 4-row self-propelled bunker harvesters, mainly because of the higher number of machines passes. The average and maximum load per tire was much less in the Smaragd concepts, about 4 times less on average and 6 times less for the maximum. The average contact pressure index $CPI$ per tire and maximum contact pressure index in field were all above the recommended limit of 35 kPa for regular soils. Also, the selected tires of 0.3 m wide and 0.7 m diameter for the smaller units in the Smaragd concepts 6.3 and 8.3 may not be optimal and tire selection requires attention, though also, the model should be equipped with better indicators for soil compaction.

***Table 10*** *Performance indicators of the transport units within the manually optimized concepts 1.2, 6.3 and 8.3.*

| Concept | | 1.2 | 6.3 | 8.3 |
|---|---|---|---|---|
| **Performance indicator** | **Unit** | **Conventional 4-row self-propelled bunker harvester** | **Smaragd 1-row harvester** | **Smaragd 2-row harvester** |
| $e_{t,f}$ | [%] | 88% | 63% | 74% |
| $e_{t,r}$ | [%] | - | 24% | 32% |
| $T_s$ total time individual machines per ha | [h ha$^{-1}$] | 3.0 | 17.3 | 12.3 |
| Total wait time field transport $\sum T_{w,f,i}$ | [h] | 1.42 | 15.51 | 7.57 |
| Total wait time road transport $\sum T_{w,r,i}$ | [h] | 0 | 31.90 | 20.34 |
| Number of filled field transports | [-] | 11 | 104 | 102 |
| Number of filled road transports | [-] | 0 | 21 | 21 |
| Percentage of field used for traffic | [%] | 77.9 | 9.5 | 9.5 |
| Average number of tire passages per track | [-] | 3.9 | 35.6 | 21.2 |
| Highest number of tire passages in field | [-] | 41 | 50 | 32 |
| Average total weight per track | [tonnes] | 17.1 | 35.8 | 23.2 |
| Average load per tire | [tonnes] | 4.4 | 1.0 | 1.1 |
| Highest tire load in field | [tonnes] | 9.0 | 1.5 | 1.5 |
| Average contact pressure index per tire | [kN m$^{-2}$] | 41.0 | 52.0 | 56.8 |
| Highest contact pressure index in field | [kN m$^{-2}$] | 109.0 | 80.4 | 80.4 |

## 5.4 Economical results

The model output was used to calculate the economic results per concept. As mentioned in paragraph 4.4 the economic calculations were divided in three categories, mechanisation, energy and labour costs. Figure 13 shows the economic results (€/ha) of the potato harvest for the conventional concepts in case the entire field of 6 hectares is harvested. The self-propelled harvester requires less time per hectare, which is reflected in the lowest labour costs. The energy costs are also higher, which relates to the power required for this type of mechanisation. The mechanisation is also more expensive. In Figure 13 the operation time per concept were stated.

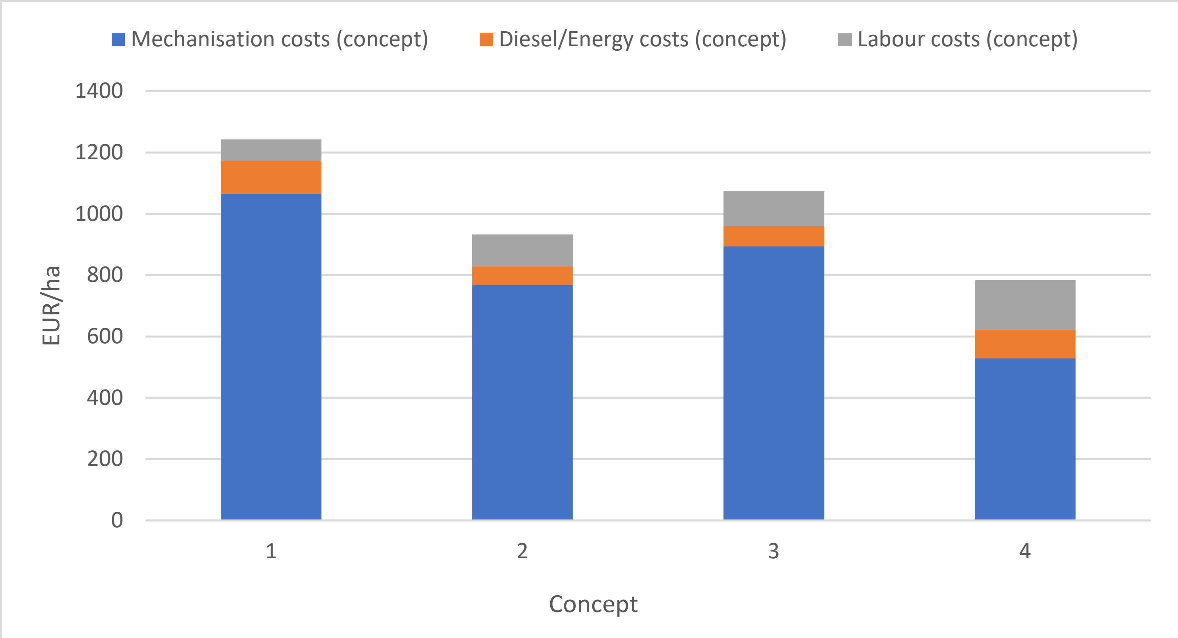



***Figure 13*** *Economic outcome per conventional concept. Stacking mechanisation, energy and labour costs (in EUR/ha for the potato harvest of the 6-hectare field).*

The SMARAGD concepts represent two differences, the number of rows and the size of the buffer. The economic results represent the differences in time needed due to the lower buffer capacity of the harvester (concepts 5 & 7), and for both the single (concepts 5 & 6) and 2-row harvester (concepts 7 & 8). The additional row further decreases the time of operation and therefore the costs of the total operation. The concepts are quite similar in mechanisation. Therefore, the time of the operation and the operating width had the biggest effect on the outcome. The results are included in Figure 14.

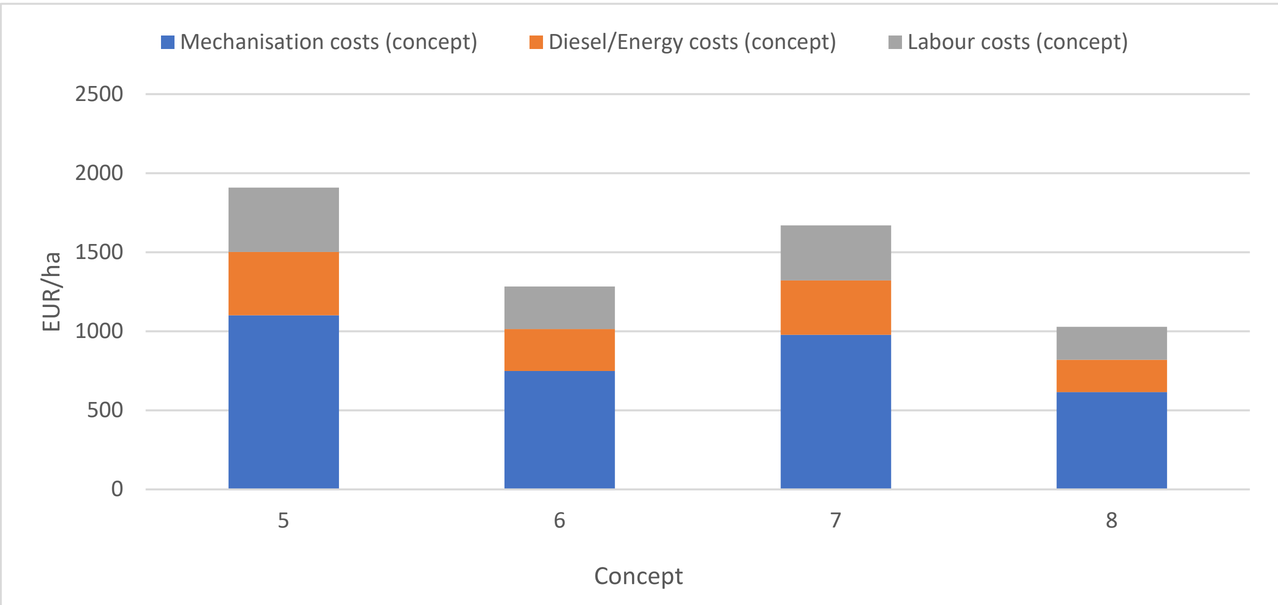



***Figure 14*** *Economic outcome per Smaragd concept. Stacking mechanisation, energy and labour costs (in EUR/ha for the potato harvest of the 6-hectare field).*

The result of the economic evaluation is that the Smaragd concepts with 500 kg buffer can compete with the 4-row selfpropelled harvester. In theory the Smaragd concepts could improve further. The labour requirement is based on the legal requirement of an human observer at the field. If no observer is needed the labour costs could be reduced. This making the Smaragd concept economically viable in comparison to the conventional 4-row self-propelled scenario. The capacity of the self-propelled 4-row harvester is significantly higher.as the Smaragd scenarios with 500 kg buffer (number 6 and 8). To achieve the same capacity for scenarios 6 and 8 would require 5 to 6 harvesters. A potential benefit would be that additional machines on the same field would not require additional observers.

**The optimizing effect**
In addition, the optimized concepts were also calculated. The optimization has a significant effect on the costs of the harvest of the modelled potato field. The economic costs of the Smaragd concepts are lower than the conventional concepts both for the single (concept 6) and double row harvester (concept 8). The results are shown in Figure 15.

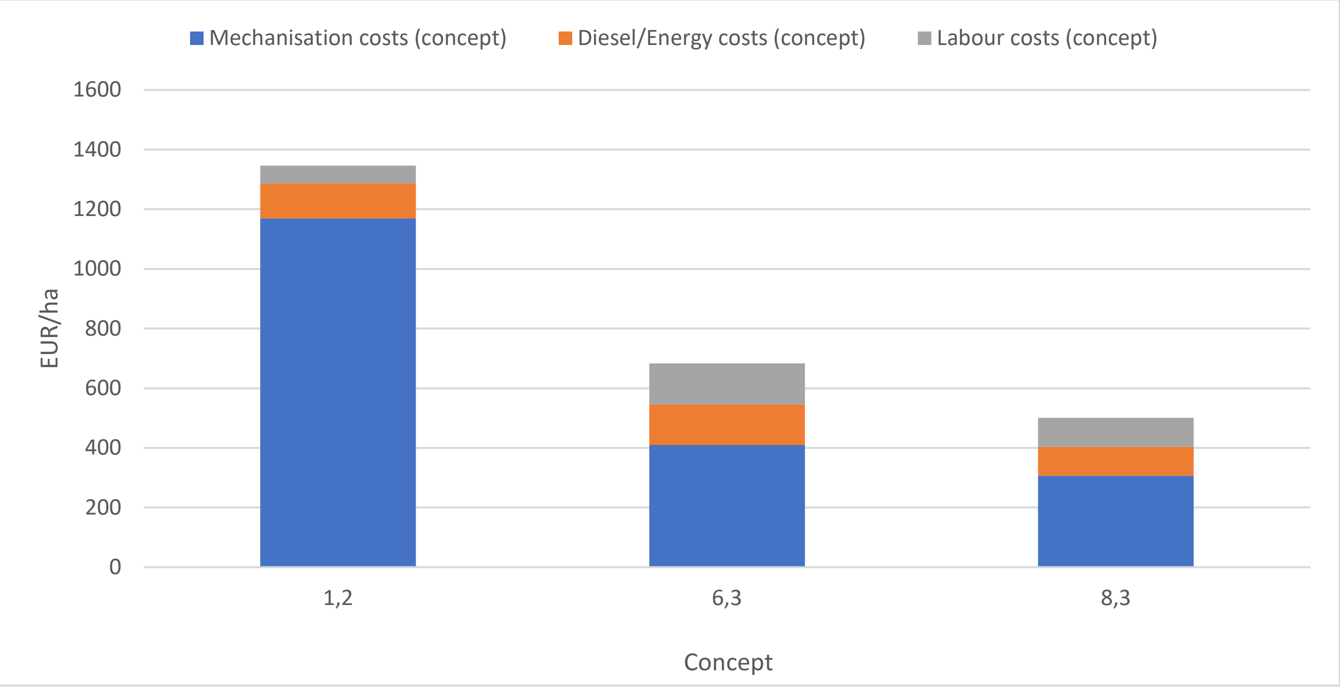



***Figure 15*** *Economic outcome for the optimized concepts. Stacking mechanisation, energy and labour costs (in EUR/ha for the potato harvest of the 6-hectare field).*

## 5.5 Operation times

The operation times of the model were examined as part of the economic evaluation. The KWIN-AGV (2018) uses operation times as part of the gross margin calculations. This data is mentioned next to the gross margins per crop in the KWIN-AGV (2018). In Table 11 the operation times from the simulations and the operation times from KWIN-AGV (2018) are given for the different concepts.
The calculated operation times of the simulation model are pure hours needed per hectare for the operation. In this case harvesting. The operation times used for the KWIN-AGV 2018 are pure operation time and some additional time, for example downtime (7%), off-loading time, time driving to and from the field and preparation and set-up time. For automated harvesting technology no operation times are stated in the KWIN-AGV database.

***Table 11*** *Comparison model versus KWIN-AGV 2018.*

| Scenario | Model | KWIN-AGV 2018[1] | Unit |
|---|---|---|---|
| 1. Conventional 3m – 4 rows | 1.16 | 2 | hours/ha |
| 2. Conventional – 1.5 m – 2 row | 1.74 | 3 | hours/ha |
| 3. Conventional – 1.5 m – 2 row - CTF | 1.90 | 3 | hours/ha |
| 4. CTF - 2 rows trailed harvester, one crate | 2.68 | 3 | hours/ha |
| 5. and 6. SMARAGD – 1 row harvester – 100 / 500 kg buffer | 10.16 / 6.73 | - | hours/ha |
| 7. and 8. SMARAGD – 2 row harvester – 100 / 500 kg buffer | 8.73 / 5.22 | - | hours/ha |

1 KWIN-AGV database values (not published)

# 6 Discussion

The research was done in an iterative manner to quickly see and explore the possibilities of using the discrete event simulation model to simulate the logistics of machine movements and operation times on a field for a potato harvest operation. For that reason, not all comparisons were done for all concepts and the results was not compared to pilots in the field also because an autonomous potato harvester is not yet in operation.

In the original concept 4a (Trailed harvester with CTF – unloading in crates – no buffer) the simulation resulted in extremely high waiting time for the harvester. Due to the CTF system only one machine could pass a lane, which resulted in no transport available. With adding a buffer of one crate (1200 kg) on the harvester, the model outcomes became more in line with what is customary in practice.
The best guess input for the default Smaragd concepts resulted in quite high Total operation times, compared with the conventional concepts, due to long waiting time of the harvester for the Transport unit. This already proves the value of model experiments prior to prototype experiments.

In the Sensitivity analysis is chosen to vary four input parameters, namely Buffer capacity, Buffer threshold, number of Transport units and Transport capacity to reduce the total operation time. These are selected because they were expected to have a relevant effect to reduce the waiting time for the harvester. The tested ranges are chosen from a practical point of view. Theoretically the ranges could be wider, but in that case they will mostly have also a negative effect on soil compaction, e.g., a higher buffer or transport capacity. In addition to the chosen input parameters for the sensitivity analysis, there may be more parameters that can increase the field efficiency. Hartman (2019) suggests, among other things, the transport speed in field. From the analyses we derived that the amount of transport units for both the conventional mechanisation strategies and the Smaragd strategies could be decreased to two units for this particular use case (field – farm). Furthermore, we derived that the buffer threshold should be set lower to achieve high field efficiencies. In the default settings we used e.g., 80% as a threshold according to farmers practice to call a transport unit when the bunker of the harvester is about 80% full. Also, for the conventional 4-row self-propelled harvester concept (1) this threshold was too high. For the conventional 2-row concepts (2 & 3) it was about right. When the bunker of the harvester is full, the harvester has to wait until a transport unit arrives next to the harvester, which causes costly waiting times. Therefore, this threshold value is decreased to 5 and 10% for conventional concepts and Smaragd concepts respectively to optimize the different concepts.

With use of the sensitivity analysis results and by means of trial-and-error different values for the buffer capacity, buffer threshold, number of transport units and transport capacity were adjusted to obtain variants with low waiting time for the harvester for each concept. The goal to minimize the waiting time of the harvester was chosen because the running costs of the harvester are highest in a potato harvest operation. Exploratory calculations showed that the total waiting time for the harvesters can be reduced from more than 30 hours to 1.4 and 0.4 hours for the concepts 8 and 6, respectively. Even for the conventional 4-row self-propelled harvester, which is assumed to already very efficient, the waiting time reduced from 1.0 to 0.0 hours and the field efficiency increased from 65% to 76.1%. However, it is recommended to formalize the search for optimal variants because optimum will also be farm dependent with for instance differences in field size, field shape, soil type and distance to the farm. Nevertheless, it is clear that stacking can improve the performance but optimisation of the systems needs to be investigated further.

It’s interesting to see the differences between the biggest and heaviest machine (4-row self-propelled bunker harvester with two tractors with tippers) and the smallest lightest machines (one or two-row robot harvesters with two robot transport units). Concept 6 and 8 have more waiting time for the harvester, however the field efficiency is much higher than in concept 1. The gross effective capacity of these harvesting concepts ranges between 0.29 and 0.41 ha $h^{-1}$ for the one-row respectively two-row harvester. The gross effective capacity of concept 1 was 1.01 ha $h^{-1}$. Farmers tend to use the concept 1 mechanisation due to the timeliness of their operation and short period of workability. A Smaragd solution with one harvester cannot realise the same capacity as the conventional solution, however with robotic harvester one man could control more robotic harvesters at once. Just based on the capacity two or three lightweight small robotic harvest machines with adequate transportation could replace one big conventional harvester. This could also strongly reduce the waiting time for road transport units as well as field transport units, thus increase the efficiency of all elements in the harvesting concept. To quantify this, the model must be adapted to allow multiple harvesters in one field simultaneously. It is therefore recommended to extend the crop operations model to simulate concepts with multiple harvest machines in the field to allow for simultaneous operation.

The operation times given by the model were evaluated by the database with operation times of the KWIN-AGV (2018). The operation times do not match exactly. The model simulated an operation time of 1.16, 1.74, 1.90 and 2.68 hours per hectare for scenario 1-4, whereas KWIN-AGV accounts for an operation time of 2 hours per hectare for scenario 1 and 3 hours for scenario 2-4. This is due to difference in method of calculation. The model calculates the net time of the operation without time loss due to machine adjustment time, maintenance time, repair time and operator’s personal time (breaks). The KWIN-AGV 2018 uses additional downtime, run-up and expiration times, however it only accounts for the type of harvester and not for the type of system (conventional vs CTF). The only significant difference between the simulation model and KWIN-AGV 2018 was with the scenario’s with bunker, self-propelled and trailed harvesters. The model was significantly lower than the KWIN-AGV times. This is due to the efficient loading and unloading within the model, where loading, transport and unloading is sequentially just in time and where transfer capacity and transfer times are set by the user. KWIN-AGV estimates and accounts for total waiting times. The evaluation of the operation time from the model and the times given by the KWIN-AGV database do show similarities and the values are not far apart.

The economic evaluation shows that the Smaragd mechanisation strategies are much lower in costs than conventional mechanisation strategies. Mainly the mechanisation costs are much lower in the Smaragd concepts compared to the conventional concepts. The costs and the depreciation of the Smaragd concepts are best guesses, as this solution doesn’t exist yet. Also, the labour costs of the Smaragd solutions are higher than conventional. This is due to assumption that one employee is needed to observe the robots in the field and 1 employee to operate the road transport unit. In the conventional concept 1 employee is needed on the harvester and 2 employees for the field/road transport units. As the total operation time of the Smaragd concepts are much higher (20.81 hours for the 2-row harvester, 14.77 hours for the 1-row harvester and 6 hours for the conventional 4-row harvester) this results in a higher labour cost. It is expected that the employee in the Smaragd solutions can observe more than one autonomous harvester. When allowing multiple harvesters on field simultaneously it is expected that the total operation time of harvesting is decreased and therefore the labour costs of the Smaragd solutions are decreased as well. The capacity of the Smaragd-system is significantly lower. In years with not optimal weather conditions the small time window for harvesting could be an issue. The optimized scenarios would require 2 or 3 harvesters to match the capacity of a self-propelled harvester. The outcomes of the economic evaluation on mechanisation, labour and energy costs show that the value proposition of small lightweight harvest operations clearly can compete with conventional machine strategies and that the Smaragd system is economically feasible.

# 7 Conclusion and recommendations

## 7.1 Conclusion

The aim of this research was to find design parameters for lightweight autonomous potato harvest strategies (Smaragd concepts) using discrete event simulation model experiments. Four innovative Hight Tech Smaragd concepts (differing in harvest and buffer capacity) were compared in an iterative process with four conventional concepts.

In the best guess lightweight concepts (Smaragd concepts) the total operation time needed to harvest the model field (6 ha) was until 8 times longer than the conventional self-propelled harvester concept, namely 7 hours for the conventional self-propelled harvester and 32 to 61 hours in the concepts Smaragd two-row harvester- 500 kg buffer and Smaragd one-row harvester - 100 kg buffer respectively. Reason for this were the long waiting times for the harvester for transport units, because the transport units cannot pass in the same lane.

The sensitivity analysis showed that the input parameters Buffer capacity and Buffer threshold in particular are relevant input parameters for increasing the field efficiency. A higher buffer capacity (until 1200 kg) resulted in the highest Field efficiency and lowest Total waiting time for the harvester. With a lower buffer threshold, the transport unit will be signalled earlier, resulting in a lower waiting time for the harvester and thus a higher field efficiency. The use of more than 2 transport units had no added effect, but reducing it to 1 transport unit resulted in a strongly reduced field efficiency due to longer waiting times for the harvester. A higher transport capacity (range 1200 - 3600 kg) resulted in a slightly higher field efficiency.
Exploratory calculations showed that stacking optimized input parameters further improves the efficiency of the harvesting process. The total wait time of the harvester can be reduced to 0.4 and 1.4 hours for the concepts Smaragd one-row and two-row harvester, respectively. Thus, resulting in a gross effective field capacity of 0.29 and 0.41 hectare per hour and a Field Efficiency of 87.8 and 82.5% in respectively the concepts one and two-row harvesters. In comparison, the self-propelled 4 row harvester (concept 1) achieves a maximum gross effective field capacity of 0.86 (default) to 1.01 (stacked optimised) hectare per hour, a Field Efficiency of 65.0 (default) to 76.1% (stacked optimised) and total wait time of the harvester of 1.0 (default) to 0.0 (stacked optimised) hour. Thus, the concept 1 (self-propelled 4 row harvester) with default input parameters is already quite efficient.

The use of the model experiments has clearly proven the benefit of the SMARAGD crop operations model over best expert guesses for parameters of lightweight concepts for harvesting operations.

The economic evaluation of the Smaragd one-row and two-row harvester and the conventional 4 row self-propelled harvester shows that the Smaragd concepts can compete with conventional concepts. The Smaragd solutions costs about €500 – 700 per hectare compared with €1250 per hectare for the conventional solution.

## 7.2 Recommendations

From the results and discussion several recommendations resulted:

- Make the model suitable for simulating simultaneous the movements of more than one harvester (e.g., 2 autonomous harvesters) with transport units.
- Make the model flexible for choosing the optimal lane for the transport units instead of using the same lane for arrival of empty transport units and departure of harvested products
- Perform improved calculations on soil load, because the purpose of emerald is to prevent soil compaction with small light machines. --> Coupling with compaction models.
- Simulate the harvesting process for a whole farm with several potato fields. There may be bottlenecks in timeliness at farm level.
- Formalise the optimisation of the design parameters of the new Smaragd solutions using formal optimisations technology such as for example genetic optimisation or Monte Carlo optimisation.
- Validate the different input parameters where duration times are stated, as manoeuvre time, transfer time, start and stop operating time, etc. This makes the model more accurate.

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# Annex 1 Description input parameters

| Field Parameters | Unit | Explanation |
|---|---|---|
| Size | [ha] | Gross size of the field |
| Distance to farm | [km] | Distance between Start position at the field and the farm |
| Strip width | [m] | Gross width of each strip, for conventional farming 3m, for CTF 3.15m |
| Track width | [m] | In case of CTF, the track width is the extra width needed for the uncultivated drive paths. For conventional farming there are no tracks (=0m), for CTF an extra space of 0.15m is used |
| Length | [m] | Length of the gross field |
| Width | [m] | Width of the gross field |
| Yield (Potato) | [t $ha^{-1}$] | Average yield of net field. For CTF 5% higher yields are assumed. Possibly these higher yields are negatively compensated by loss of area by tracks |
| Yield Deviation | [%] | Deviation of the yield |

| Model parameters | Unit | Explanation |
|---|---|---|
| Operation mode | [-] | The simulation model is generic for all types of operations, for harvesting its set on Mass Input Operation, where the mass of the machine increases during operations. Other options are Mass Neutral Operations (e.g., tillage, howing, etc.) or Mass Output Operations (discharge of mass during operation e.g., spraying, seeding, fertilizing, etc.) |
| Transport mode | [-] | There are 4 modes of transport: 1. Combined field and road transport, 2: Separate field and road transport, 3: Road transport only and 4: No transport |
| Transfer while driving | [-] | With Yes mass is transferred between the field machine and field transport while driving, with No the machine stops first to transfer mass |
| CTF | [-] | With Yes machine and field transport movements are fixed to lanes, see picture with machines and field transport. |
| Headland buffer | [-] | With 'Yes', the field or road transport unit can transfer mass to a buffer on the headland (e.g., sugar beet pile or manure container). With 'No', the field transport unit has to wait for a road transport unit or vice versa for direct transfer. |

| Harvester | Unit | Explanation |
|---|---|---|
| Weight (empty) | [kg] | Total weight of the machine. With towed harvester is it the total weight of tractor + harvester |
| Buffer capacity | [kg] | This is the capacity of the buffer (bunker or crates) |
| Buffer Threshold | [%] | When this threshold is reached the machines starts to transfer mass to field transport units |
| Operating width | [m] | This is the operating width of the machine (4rows = 3m, 2rows=1.5m, 1row=0.75m) |
| Driving speed field | [km $h^{-1}$] | |
| Driving speed road | [km $h^{-1}$] | |
| Operating speed | [km $h^{-1}$] | |
| Transfer speed | [kg $s^{-1}$] | Transferring 8000 kg from a bunker to a trailer lasts ca 90seconds |
| Manoeuvre time | [s] | The time to manoeuvre in the field |
| Initiate time | [s] | The time to start the motor of the harvester (or tractor) |

| | | |
|---|---|---|
| Terminate time | [s] | The time to shut down the motor of the harvester (or tractor) |
| Start operating time | [s] | The time to initiate harvesting (positioning harvester, lower the digger, etc.) |
| Stop operating time | [s] | The time to stop harvesting (raise digger, stop belts, etc.) |
| Start implement time | [s] | Time when entering a row (acceleration) |
| Stop implement time | [s] | Time when leaving a row (deceleration) |
| Start transfer time | [s] | Time to initiate unloading |
| Stop transfer time | [s] | Time to stop unloading |
| Turn time | [s] | Time to turn on the headland |
| Bidirectional | [-] | Yes, if the harvester has to go back and forth in the same CTF lane (e.g., harvesting 2 rows at a time), otherwise No |
| Axle 1 | | *Set of parameters also available for Axle 2 and Axle 3* |
| Weight | [%] | Percentage of weight from empty harvester on this axle |
| Load | [%] | Percentage of weight from harvested load on this axle |
| Track width | [m] | Width between the front wheels (heart to hearth) |
| Track offset | [m] | When towing a harvester (as with conventional towed harvester in picture right) the first two axles have an offset to the left compared with the middle of the harvested area.<br>Positive value if offset is on the left, negative value if the offset is on the right |
| Tire width | [m] | |
| Tire Diameter | [m] | |

*In the concept with tippers, field transport = road transport, so parameters of road transport are not used*

| **Road transport** | **Unit** | **Description** |
|---|---|---|
| Nr. Of units | [-] | The amount of Road transport units |
| Transport Capacity | [kg] | The capacity of the road transport unit |
| Driving speed road | [km $h^{-1}$] | Driving speed at the road |
| Transfer Threshold | [%] | The minimum threshold of the transport unit at which the unit may drive to the farm |
| Transfer speed | [kg $s^{-1}$] | The unloading transfer speed of the unit |
| Start transfer time | [s] | The time needed to start unloading (detaching the crate or raising the tipper) |
| Stop transfer time | [s] | The time needed to stop unloading |

| **Field transport** | **Unit** | **Description** |
|---|---|---|
| Nr. Of units | [-] | The amount of Field transport units |
| Weight (empty) | [kg] | The weight of the Field transport units (to calculate soil pressure) |
| Transport Capacity | [kg] | The capacity of the Field transport units |
| Driving speed field | [km $h^{-1}$] | Max driving speed at the field |
| Driving speed road | [km $h^{-1}$] | If the field transport unit is also used on the road, the road driving speed is used (in the case of tippers) |
| Transfer Threshold | % | The minimum threshold of the transport unit at which the unit may drive to the road |
| Transfer speed | [kg $s^{-1}$] | The unloading transfer speed of the unit |
| Start transfer time | [s] | The time needed to start unloading (detaching the crate or raising the tipper) |
| Stop transfer time | [s] | The time needed to stop unloading |
| Turn time | [s] | The time to turn at the headland |

| | | |
|---|---|---|
| Bidirectional | [-] | Yes, if the field transport unit can drive backwards at the same lane (e.g., autonomous harvester with a crate), otherwise no (conventional) |
| Row Offset | m | In case of CTF, this is the distance between middle of harvest operation and middle of transport unit |
| Offset | m | In case of conventional, this is the distance between middle of harvest operation and middle of transport unit |
| Axle 1 | | *Set of parameters also available for Axle 2, Axle 3 and Axle 4 if present.* |
| Weight | [%] | |
| Load | [%] | |
| Track width | [m] | |
| Track offset | [m] | |
| Tire width | [m] | |
| Tire Diameter | [m] | |

| **Storage parameters** | | Directly harvesting in crates means less time spent in storage, compared with harvesting in tippers and overloading in crates in storage |
|---|---|---|
| Transfer speed | [kg $s^{-1}$] | |
| Start transfer time | [s] | |
| Stop transfer time | [s] | |

# Annx 2 Description output parameters

| Parameter | Unit | Description |
|---|---|---|
| Gross field size | [ha] | Area enclosed by the polygon defining the boundaries of the field |
| Net field size | [ha] | The operated/processed area with products/crop |
| Total operation time | [h] | Total time in operation in the field, working on the planned crop operation |
| Effective operation time | [h] | Time spent on the core function, actual harvesting in this case |
| Gross theoretical field time | [h] | Effective operation time needed for the gross field size |
| Net theoretical field time | [h] | Effective operation time needed for the net field size |
| Gross field capacity | [ha/h] | Gross field size divided by total operation time |
| Net field capacity | [ha/h] | Net field size divided by total operation time |
| Field efficiency | [%] | Net theoretical field time divided by total operation time |
| Total time transport | [h] | Total time the transport units are occupied |
| Total time road transport | [h] | Total time the road transport units are occupied |
| Total time machine and road transport (h | [h] | Total occupation time of all units including waiting time |
| Total time per gross ha | [h] | Total occupation time per ha using gross field size |
| Total time per net ha | [h] | Total occupation time per ha of the processed area |
| Total wait time machine | [h] | Wait time of the machine |
| Total wait time transport | [h] | Wait time of all field transport units |
| Total wait time road transport | [h] | Wait time of all road transport units |
| Sum of all in field wait time | [h] | Total wait time for all units involved |
| Transport efficiency | [%] | Gross transport time minus total wait time transport units over gross transport time |
| Transport efficiency road | [%] | Gross road transport time minus total wait time road transport units over gross road transport time |
| Additional units of transport needed | [-] | If minimum in number of waiting units is greater than zero, this is the estimated number of transport units not needed |
| Additional units of road transport needed | [-] | If minimum in number of waiting units is greater than zero, this is the estimated number of road transport units not needed |
| Matter in storage | [tonnes] | Total fresh weight harvested |
| Matter from storage | [tonnes] | |
| **Soil parameters** | | |
| Traffic-ridden area | [%] | Area touched by traffic |
| Area overloaded | [%] | Percentage of total area that received a maximum load above 35 $kN/m^2$ |
| Tracks overloaded | [%] | Percentage of traffic-ridden area that received a maximum load above 35 $kN/m^2$ |
| Average tire passages | [-] | Average number of tire passages per spatial cell in field, each axle passage counts as one |
| Average tire passages per track | [-] | Average number of tire passages per spatial cell in traffic-ridden area |
| Maximum tire passages | [-] | Maximum count of number of tire passages in spatial cells of field |
| Average total weight in field | [tonnes] | Average weight per spatial cell in the field |
| Average total weight in traffic area | [tonnes] | Average weight per spatial cell in the traffic-ridden area |
| Maximum total weight | [tonnes] | Maximum total weight in a spatial cell anywhere in the field |
| Average tire load | [tonnes] | Average tire load in field |
| Average maximum tire load | [tonnes] | Average of the maximum tire load per spatial cell in the traffic-ridden area |
| Maximum tire load | [tonnes] | Maximum tire load that occurred during the operation |
| Average total contact pressure index in field | [$kN/m^2$] | Spatial average of summed contact pressure indices in field |
| Average total contact pressure index per track | [$kN/m^2$] | Spatial average of summed contact pressure indices in traffic-ridden area |

| | | |
|---|---|---|
| Maximum total contact pressure index | [kN/m$^2$] | Maximum spatial summed contact pressure index in field |
| Average contact pressure index | [kN/m$^2$] | Spatial average contact pressure index in field per spatial average tire passage |
| Average maximum contact pressure index | [kN/m$^2$] | Spatial average maximum contact pressure index in field per spatial average tire passage |
| Maximum contact pressure index | [kN/m$^2$] | Overall maximum contact pressure index in field |

# Annex 3 Concept – input ‘available’ tech

| **Concept number** | | **1** | **2** | **3** | **4** |
|---|---|---|---|---|---|
| **Concept name** | | Conventional - 3m | 1p5 Conventional -no CTF | 1p5 Conventional - with CTF | CTF + Trailed harvester, one crate |
| **Description** | | 4-row self-propelled, buffer, unloading while driving | 2-row trailed, bunker, unload while driving | As #2, only with CTF, and unloading at headland only | Harvest into crates |
| **Field Parameters** | **Unit** | | | | |
| Size | [ha] | 6 | 6 | 6 | 6 |
| Distance to farm | [km] | 1 | 1 | 1 | 1 |
| Strip width | [m] | 3 | 3 | 3.15 | 3.15 |
| Track width | [m] | 0 | 0 | 0.15 | 0.15 |
| Length | [m] | 300 | 300 | 300 | 300 |
| Width | [m] | 200 | 200 | 200 | 200 |
| Yield of the potato crop | [t ha-1] | 42 | 42 | 44.1 | 44.1 |
| Yield Deviation | [%] | 5 | 5 | 5 | 5 |
| Selected Field for simulation | [-] | 1 | 1 | 1 | 1 |
| Selected Rotation year | [-] | 1 | 1 | 1 | 1 |
| Selected Crop Type | [-] | 5 | 5 | 5 | 5 |

| **Model parameters** | **Unit** | | | | |
|---|---|---|---|---|---|
| Operation mode | [-] | 1 | 1 | 1 | 1 |
| Transport mode | [-] | 1 | 1 | 1 | 1 |
| Transfer while driving | [-] | 0 | 1 | 0 | 1 |
| CTF applied? | [-] | 0 | 0 | 1 | 1 |
| Strip intercropping applied | [-] | 0 | 0 | 0 | 0 |
| Headland buffer | [-] | 2 | 2 | 2 | 2 |
| Headland buffer capacity | [t] | 20 | 20 | 20 | 20 |

**Machine Parameters**

| **Harvester** | **Unit** | | | | |
|---|---|---|---|---|---|
| Weight (empty) | [kg] | 24000 | 15500 | 15500 | 12500 |
| Buffer capacity | [kg] | 8000 | 6000 | 6000 | 1200 |
| Buffer Threshold | [%] | 80 | 80 | 80 | 80 |
| Operating width | [m] | 3 | 1.5 | 1.5 | 1.5 |
| Driving speed field | [km $h^{-1}$] | 6 | 6 | 6 | 6 |

| **Concept number** | | **1** | **2** | **3** | **4** |
|---|---|---|---|---|---|
| **Concept name** | | Conventional - 3m | 1p5 Conventional -no CTF | 1p5 Conventional - with CTF | CTF + Trailed harvester, one crate |
| Driving speed road | [km h$^{-1}$] | 30 | 30 | 30 | 30 |
| Operating speed | [km h$^{-1}$] | 4 | 4 | 4 | 4 |
| Transfer speed | [kg s$^{-1}$] | 87.5 | 87.5 | 87.5 | 87.5 |
| Transfer speed deviation | [%] | 5 | 5 | 5 | 5 |
| Manoeuvre time | [s] | 6.5 | 6.5 | 6.5 | 6.5 |
| Manoeuvre time deviation | [s] | 4.44 | 4.44 | 4.44 | 4.44 |
| Initiate time | [s] | 30 | 30 | 30 | 30 |
| Terminate time | [s] | 30 | 30 | 30 | 30 |
| Start operating time | [s] | 30 | 30 | 30 | 30 |
| Stop operating time | [s] | 10 | 10 | 10 | 10 |
| Start implement time | [s] | 1.9 | 1.9 | 1.9 | 1.9 |
| Stop implement time | [s] | 2.7 | 2.7 | 2.7 | 2.7 |
| Start transfer time | [s] | 5.8 | 5.8 | 5.8 | 5.8 |
| Stop transfer time | [s] | 7.2 | 7.2 | 7.2 | 7.2 |
| Turn time | [s] | 5 | 5 | 5 | 5 |
| Bidirectional | [-] | 2 | 2 | 1 | 1 |
| Axle 1 | | | | | |
| Weight | [%] | 40 | 33.33 | 33.33 | 33.33 |
| Load | [%] | 10 | 0 | 0 | 0 |
| Track width | [m] | 3 | 1.9 | 3.15 | 3.15 |
| Track offset | [m] | 0 | 1.125 | 0 | 0 |
| Tire width | [m] | 0.25 | 0.54 | 0.3 | 0.3 |
| Tire Diameter | [m] | 1.8 | 1.4 | 1.4 | 1.4 |
| Axle 2 | | | | | |
| Weight | [%] | 60 | 33.33 | 33.33 | 33.33 |
| Load | [%] | 90 | 50 | 50 | 50 |
| Track width | [m] | 2 | 1.9 | 3.15 | 3.15 |
| Track offset | [m] | 0 | 1.125 | 0 | 0 |
| Tire width | [m] | 1 | 0.65 | 0.3 | 0.3 |
| Tire Diameter | [m] | 1.8 | 1.9 | 1.9 | 1.9 |
| Axle 3 | | | | | |
| Weight | [%] | 0 | 33.33 | 33.33 | 33.33 |
| Load | [%] | 0 | 50 | 50 | 50 |
| Track width | [m] | 0 | 2.3 | 3.15 | 3.15 |
| Track offset | [m] | 0 | 0.375 | 0 | 0 |
| Tire width | [m] | 0 | 0.6 | 0.3 | 0.3 |
| Tire Diameter | [m] | 0 | 1.2 | 1.2 | 1.2 |
| **Transport Parameters** | **Unit** | | | | |
| **Road Transport** | | | | | |
| Nr. Of units | [-] | 0 | 0 | 0 | 0 |
| Transport Capacity | [kg] | 0 | 0 | 0 | 0 |
| Driving speed road | [km h$^{-1}$] | 0 | 0 | 0 | 0 |
| Transfer Threshold | [%] | 0 | 0 | 0 | 0 |
| Transfer speed | [kg s$^{-1}$] | 0 | 0 | 0 | 0 |

| **Concept number** | | **1** | **2** | **3** | **4** |
|---|---|---|---|---|---|
| **Concept name** | | Conventional - 3m | 1p5 Conventional -no CTF | 1p5 Conventional - with CTF | CTF + Trailed harvester, one crate |
| Transfer speed deviation | [%] | 0 | 0 | 0 | 0 |
| Start transfer time | [s] | 0 | 0 | 0 | 0 |
| Stop transfer time | [s] | 0 | 0 | 0 | 0 |
| **Field Transport** | | | | | |
| Nr. of units | [-] | 2 | 2 | 2 | 3 |
| Weight (empty) | [kg] | 17000 | 17000 | 17000 | 9000 |
| Transport Capacity | [kg] | 18000 | 18000 | 18000 | 7200 |
| Driving speed field | [km $h^{-1}$] | 15 | 15 | 15 | 15 |
| Driving speed road | [km $h^{-1}$] | 30 | 30 | 30 | 30 |
| Transfer Threshold | [%] | 90 | 90 | 90 | 90 |
| Transfer speed | [kg s-1] | 16 | 16 | 16 | 16 |
| Transfer speed deviation | [%] | 5 | 5 | 5 | 5 |
| Start transfer time | [s] | 120 | 120 | 120 | 60 |
| Stop transfer time | [s] | 30 | 30 | 30 | 30 |
| Turn time | [-] | 5 | 5 | 5 | 5 |
| Bidirectional | [-] | 2 | 2 | 2 | 2 |
| Row Offset | [m] | 0 | 0 | 7.05 | 7.05 |
| Offset | [m] | 4.5 | 4.5 | 0 | 0 |
| | | | | | |
| Axle1 | | | | | |
| Weight | [%] | 25 | 25 | 25 | 35 |
| Load | [%] | 0 | 0 | 0 | 0 |
| Track width | [m] | 1.9 | 1.9 | 1.9 | 3.15 |
| Track offset | [m] | 0 | 0 | 0 | 0 |
| Tire width | [m] | 0.54 | 0.54 | 0.54 | 0.3 |
| Tire Diameter | [m] | 1.4 | 1.4 | 1.4 | 1.4 |
| Axle2 | | | | | |
| Weight | [%] | 25 | 25 | 25 | 35 |
| Load | [%] | 33.3 | 33.3 | 33.3 | 50 |
| Track width | [m] | 1.9 | 1.9 | 1.9 | 3.15 |
| Track offset | [m] | 0 | 0 | 0 | 0 |
| Tire width | [m] | 0.65 | 0.65 | 0.65 | 0.3 |
| Tire Diameter | [m] | 1.9 | 1.9 | 1.9 | 1.4 |
| Axle 3 | | | | | |
| Weight | [%] | 25 | 25 | 25 | 30 |
| Load | [%] | 33.33 | 33.33 | 33.33 | 50 |
| Track width | [m] | 1.9 | 1.9 | 1.9 | 3.15 |
| Track offset | [m] | 0 | 0 | 0 | 0 |
| Tire width | [m] | 0.65 | 0.65 | 0.65 | 0.3 |
| Tire Diameter | [m] | 1.3 | 1.3 | 1.3 | 1.8 |
| Axle 4 | | | | | |
| Weight | [%] | 25 | 25 | 25 | 0 |
| Load | [%] | 33.3 | 33.3 | 33.3 | 0 |
| Track width | [m] | 1.9 | 1.9 | 1.9 | 0 |
| Track offset | [m] | 0 | 0 | 0 | 0 |

| Concept number | | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Concept name | | Conventional - 3m | 1p5 Conventional -no CTF | 1p5 Conventional - with CTF | CTF + Trailed harvester, one crate |
| Tire width | [m] | 0.65 | 0.65 | 0.65 | 0 |
| Tire Diameter | [m] | 1.3 | 1.3 | 1.3 | 0 |
| **Storage parameters** | | | | | |
| Transfer speed | [kg $s^{-1}$] | 16 | 16 | 16 | 16 |
| Transfer speed deviation | [%] | 5 | 5 | 5 | 5 |
| Start transfer time | [s] | 120 | 120 | 120 | 60 |
| Stop transfer time | [s] | 120 | 120 | 120 | 30 |

# Annex 4 Concept – input 'new' tech

| **Concept number** | | **Smaragd 5** | **Smaragd 6** | **Smaragd 7** | **Smaragd 8** |
|---|---|---|---|---|---|
| **Concept name** | | one-row harvester, 100 kg buffer | one-row harvester, 500 kg buffer | two-row harvester, 100 kg buffer | two-row harvester, 500 kg buffer |
| **Field Parameters** | **Unit** | | | | |
| Size | [ha] | 6 | 6 | 6 | 6 |
| Distance to farm | [km] | 1 | 1 | 1 | 1 |
| Strip width | [m] | 3.15 | 3.15 | 3.15 | 3.15 |
| Track width | [m] | 0.15 | 0.15 | 0.15 | 0.15 |
| Length | [m] | 300 | 300 | 300 | 300 |
| Width | [m] | 200 | 200 | 200 | 200 |
| Yield of the crop (Potato in this case) | [t $ha^{-1}$] | 44.1 | 44.1 | 44.1 | 44.1 |
| Yield Deviation | [%] | 5 | 5 | 5 | 5 |
| Selected Field for simulation | [-] | 1 | 1 | 1 | 1 |
| Selected Rotation year | [-] | 1 | 1 | 1 | 1 |
| Selected Crop Type | [-] | 5 | 5 | 5 | 5 |
| **Model parameters** | **Unit** | | | | |
| Operation mode | [-] | 1 | 1 | 1 | 1 |
| Transport mode | [-] | 2 | 2 | 2 | 2 |
| Transfer while driving | [-] | 1 | 1 | 1 | 1 |
| CTF applied? | [-] | 1 | 1 | 1 | 1 |
| Strip intercropping applied | [-] | 0 | 0 | 0 | 0 |
| Headland buffer | [-] | 2 | 2 | 2 | 2 |
| Headland buffer capacity | [t] | 20 | 20 | 20 | 20 |
| **Machine Parameters** | | | | | |
| **Harvester** | **Unit** | | | | |
| Weight (empty) | [kg] | 2500 | 3000 | 3000 | 3500 |
| Buffer capacity | [kg] | 100 | 500 | 100 | 500 |
| Buffer Threshold | [%] | 80 | 80 | 80 | 80 |
| Operating width | [m] | 0.75 | 0.75 | 1.5 | 1.5 |
| Driving speed field | [km $h^{-1}$] | 6 | 6 | 6 | 6 |
| Driving speed road | [km $h^{-1}$] | 30 | 30 | 30 | 30 |
| Operating speed | [km $h^{-1}$] | 4 | 4 | 3 | 3 |
| Transfer speed | [kg $s^{-1}$] | 87.5 | 87.5 | 87.5 | 87.5 |
| Transfer speed deviation | [%] | 5 | 5 | 5 | 5 |
| Manoeuvre time | [s] | 5.5 | 5.5 | 5.5 | 5.5 |
| Manoeuvre time deviation | [s] | 2 | 2 | 2 | 2 |
| Initiate time | [s] | 90 | 90 | 90 | 90 |
| Terminate time | [s] | 10 | 10 | 10 | 10 |
| Start operating time | [s] | 32 | 32 | 30 | 30 |
| Stop operating time | [s] | 10 | 10 | 10 | 10 |

| Concept number | | Smaragd 5 | Smaragd 6 | Smaragd 7 | Smaragd 8 |
|---|---|---|---|---|---|
| **Concept name** | | one-row harvester, 100 kg buffer | one-row harvester, 500 kg buffer | two-row harvester, 100 kg buffer | two-row harvester, 500 kg buffer |
| Start implement time | [s] | 1.9 | 1.9 | 1.9 | 1.9 |
| Stop implement time | [s] | 2.7 | 2.7 | 2.7 | 2.7 |
| Start transfer time | [s] | 5.8 | 5.8 | 5.8 | 5.8 |
| Stop transfer time | [s] | 7.2 | 7.2 | 7.2 | 7.2 |
| Turn time | [s] | 8 | 8 | 8 | 8 |
| Bidirectional | [-] | 1 | 1 | 1 | 1 |
| Axle 1 | | | | | |
| Weight | [%] | 50 | 50 | 50 | 50 |
| Load | [%] | 50 | 50 | 50 | 50 |
| Track width | [m] | 3.15 | 3.15 | 3.15 | 3.15 |
| Track offset | [m] | 0 | 0 | 0 | 0 |
| Tire width | [m] | 0.3 | 0.3 | 0.3 | 0.3 |
| Tire Diameter | [m] | 0.7 | 0.7 | 0.7 | 0.7 |
| Axle 2 | | | | | |
| Weight | [%] | 50 | 50 | 50 | 50 |
| Load | [%] | 50 | 50 | 50 | 50 |
| Track width | [m] | 3.15 | 3.15 | 3.15 | 3.15 |
| Track offset | [m] | 0 | 0 | 0 | 0 |
| Tire width | [m] | 0.3 | 0.3 | 0.3 | 0.3 |
| Tire Diameter | [m] | 0.7 | 0.7 | 0.7 | 0.7 |
| Axle 3 | | | | | |
| Weight | [%] | 0 | 0 | 0 | 0 |
| Load | [%] | 0 | 0 | 0 | 0 |
| Track width | [m] | 0 | 0 | 0 | 0 |
| Track offset | [m] | 0 | 0 | 0 | 0 |
| Tire width | [m] | 0 | 0 | 0 | 0 |
| Tire Diameter | [m] | 0 | 0 | 0 | 0 |

| Transport Parameters | Unit | | | | |
|---|---|---|---|---|---|
| **Road Transport** | | | | | |
| Nr. Of units | [-] | 2 | 2 | 2 | 2 |
| Transport Capacity | [kg] | 12000 | 12000 | 12000 | 12000 |
| Driving speed road | [km $h^{-1}$] | 30 | 30 | 30 | 30 |
| Transfer Threshold | [%] | 90 | 90 | 90 | 90 |
| Transfer speed | [kg $s^{-1}$] | 16 | 16 | 16 | 16 |
| Transfer speed deviation | [%] | 5 | 5 | 5 | 5 |
| Start transfer time | [s] | 5 | 5 | 5 | 5 |
| Stop transfer time | [s] | 5 | 5 | 5 | 5 |
| **Field Transport** | | | | | |
| Nr. of units | [-] | 5 | 5 | 5 | 5 |
| Weight (empty) | [kg] | 3500 | 3500 | 3500 | 3500 |
| Transport Capacity | [kg] | 1200 | 1200 | 1200 | 1200 |
| Driving speed field | [km $h^{-1}$] | 8 | 8 | 8 | 8 |
| Driving speed road | [km $h^{-1}$] | 0 | 0 | 0 | 0 |
| Transfer Threshold | [%] | 90 | 90 | 90 | 90 |
| Transfer speed | [kg $s^{-1}$] | 40 | 40 | 40 | 40 |

| **Concept number** | | **Smaragd 5** | **Smaragd 6** | **Smaragd 7** | **Smaragd 8** |
|---|---|---|---|---|---|
| **Concept name** | | one-row harvester, 100 kg buffer | one-row harvester, 500 kg buffer | two-row harvester, 100 kg buffer | two-row harvester, 500 kg buffer |
| Transfer speed deviation | [%] | 5 | 5 | 5 | 5 |
| Start transfer time | [s] | 30 | 30 | 30 | 30 |
| Stop transfer time | [s] | 10 | 10 | 10 | 10 |
| Turn time | [-] | 5 | 5 | 5 | 5 |
| Bidirectional | [-] | 1 | 1 | 1 | 1 |
| Row Offset | [m] | 0 | 0 | 0 | 0 |
| Offset | [m] | 0 | 0 | 0 | 0 |
| | | | | | |
| Axle1 | | | | | |
| Weight | [%] | 50 | 50 | 50 | 50 |
| Load | [%] | 50 | 50 | 50 | 50 |
| Track width | [m] | 3.15 | 3.15 | 3.15 | 3.15 |
| Track offset | [m] | 0 | 0 | 0 | 0 |
| Tire width | [m] | 0.3 | 0.3 | 0.3 | 0.3 |
| Tire Diameter | [m] | 0.6 | 0.6 | 0.6 | 0.6 |
| Axle2 | | | | | |
| Weight | [%] | 50 | 50 | 50 | 50 |
| Load | [%] | 50 | 50 | 50 | 50 |
| Track width | [m] | 3.15 | 3.15 | 3.15 | 3.15 |
| Track offset | [m] | 0 | 0 | 0 | 0 |
| Tire width | [m] | 0.3 | 0.3 | 0.3 | 0.3 |
| Tire Diameter | [m] | 0.6 | 0.6 | 0.6 | 0.6 |
| Axle 3 | | | | | |
| Weight | [%] | 0 | 0 | 0 | 0 |
| Load | [%] | 0 | 0 | 0 | 0 |
| Track width | [m] | 0 | 0 | 0 | 0 |
| Track offset | [m] | 0 | 0 | 0 | 0 |
| Tire width | [m] | 0 | 0 | 0 | 0 |
| Tire Diameter | [m] | 0 | 0 | 0 | 0 |
| Axle 4 | | | | | |
| Weight | [%] | 0 | 0 | 0 | 0 |
| Load | [%] | 0 | 0 | 0 | 0 |
| Track width | [m] | 0 | 0 | 0 | 0 |
| Track offset | [m] | 0 | 0 | 0 | 0 |
| Tire width | [m] | 0 | 0 | 0 | 0 |
| Tire Diameter | [m] | 0 | 0 | 0 | 0 |
| **Storage parameters** | | | | | |
| Transfer speed | [kg $s^{-1}$] | 16 | 16 | 16 | 16 |
| Transfer speed deviation | [%] | 5 | 5 | 5 | 5 |
| Start transfer time | [s] | 60 | 60 | 60 | 60 |
| Stop transfer time | [s] | 30 | 30 | 30 | 30 |

# Annex 5 KWIN-AGV 2018 data

| Amount | Description | | Replacement costs (EUR excl. VAT) Low | High | Interest rate | Depreciation | Maintenance | Total cost (year) | utilization (year) |
|---|---|---|---|---|---|---|---|---|---|
| **1. Conventional 3m – 4 rows** | | | | | | | | | |
| 3x | Tractor 4-wd | 70-80 kW | 42000 | 66000 | 2.20% | 7.5% | 4.0% | 13.7% | 600 hours |
| 3x | Tipper hydraulic, tandem | 18 ton | 25500 | 40000 | 2.20% | 5.6% | 2.0% | 9.8% | 200 hours |
| 1x | Bunker harvester selfpropelled | 4-rows | 410000 | 545000 | 2.20% | 11.3% | 3.6% | 17.1% | 120 ha |
| **2. Conventional – 1.5 m – 2 row** | | | | | | | | | |
| 2x | Tractor 4-wd | 70-80 kW | 42000 | 66000 | 2.20% | 7.5% | 4.0% | 13.7% | 600 hours |
| 2x | Tipper hydraulic, tandem | 18 ton | 25500 | 40000 | 2.20% | 5.6% | 2.0% | 9.8% | 200 hours |
| 1x | Tractor 4-wd | 80-100 kW | 57000 | 95000 | 2.20% | 7.5% | 4.0% | 13.7% | 600 hours |
| 1x | Bunker harvester trailed | 2-rows | 90500 | 135000 | 2.20% | 11.3% | 3.1% | 16.6% | 80 ha |
| **3. Conventional – 1.5 m – 2 row - CTF** | | | | | | | | | |
| 2x | Tractor 4-wd | 70-80 kW | 42000 | 66000 | 2.20% | 7.5% | 4.0% | 13.7% | 600hours |
| 2x | Tipper hydraulic, tandem | 18 ton | 25500 | 40000 | 2.20% | 5.6% | 2.0% | 9.8% | 200 hours |
| 1x | Tractor 4-wd | 80-100 kW | 57000 | 95000 | 2.20% | 7.5% | 4.0% | 13.7% | 600 hours |
| 1x | Bunker harvester trailed | 2-rows | 102000 | 160000 | 2.20% | 11.3% | 3.1% | 16.6% | 80 ha |
| **4. CTF - 2 rows trailed harvester, one crate** | | | | | | | | | |
| 2x | Tractor 4-wd | 70-80 kW | 42000 | 66000 | 2.20% | 7.5% | 4.0% | 13.7% | 600 hours |
| 2x | Trailer box crates | 8 kisten | 20000 | 30000 | 2.20% | 7.5% | 2.5% | 12.2% | 100 hours |
| 1x | Tractor 4-wd | 80-100 kW | 57000 | 95000 | 2.20% | 7.5% | 4.0% | 13.7% | 600 hours |
| 1x | Wagenrooier getrokken | 2-rows | 90000 | 120000 | 2.20% | 11.3% | 3.1% | 16.6% | 80 ha |
| **5. and 6. SMARAGD – 1 row harvester – 100 and 500 kg buffer** | | | | | | | | | |
| 3x | Robotti | 75 kW | 75000 | 120000 | 2.20% | 7.5% | 4.0% | 13.7% | 600 hours |
| 2x | Tractor mounted forklift mast | 2000 kg | 4500 | 5500 | 2.20% | 6.0% | 2.5% | 10.7% | 100 hours |
| 1x | Harvester, simple | 1-row | 10000 | 15000 | 2.20% | 11.3% | 3.1% | 16.6% | 40 ha[1] |
| 1x | Tractor 4-wd | 70-80 kW | 42000 | 66000 | 2.20% | 7.5% | 4.0% | 13.7% | 600 hours |
| 1x | Trailer 3-axles tandem | 25 ton | 8500 | 18000 | 2.20% | 4.5% | 2.0% | 8.7% | 200 hours |

**7. and 8. SMARAGD – 2 row harvester – 100 and 500 kg buffer**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 3x | Robotti | 75 kW | 75000 | 120000 | 2.20% | 7.5% | 4.0% | 13.7% | 600 hours |
| 2x | Tractor mounted forklift mast | 2000 kg | 4500 | 5500 | 2.20% | 6.0% | 2.5% | 10.7% | 100 Hours |
| 1x | Harvester, simple | 2-rows | 15000 | 20000 | 2.20% | 11.3% | 3.1% | 16.6% | 40 ha[1] |
| 1x | Tractor 4-wd | 70-80 kW | 42000 | 66000 | 2.20% | 7.5% | 4.0% | 13.7% | 600 hours |
| 1x | Trailer 3-axles tandem | 25 ton | 8500 | 18000 | 2.20% | 4.5% | 2.0% | 8.7% | 200 hours |

1 The utilization of the harvesters for the SMARAGD scenarios is assumed to be similar and set to 40 hectares

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Report WPR-882

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