

# A Model of Field Machinery Capability and Logistics: the case of Manure Application

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## Abstract

Complex requirements imposed on the handling of animal manure calls for operational optimization of its application. This includes transport and distribution strategies based on an operational evaluation of the sequence of operations, e.g., loading at the storage site, transportation, and application in the field. Such an evaluation requires an understanding of the consequences of using various technologies in terms of labor input, system capacity, and logistics, which might result in different degrees of efficiency in the utilization of manure nutrients as well as differing effects on the environment. A modeling framework was developed for evaluating the operational performance of manure-handling machinery, given specific external and internal conditions on the farm. The knowledge base encompasses capacity and labor requirements for the application of slurry using injection or trailing hoses. Simulations show that shallow injection applicators with working widths of 6–8 m have a 35–40% higher capacity than deep/closed types with working widths of 2–3 m, and a 7–20% lower capacity than surface application. The bottleneck in the application system is the time-consuming transport part of the application process. The use of self-propelled slurry applicators connected to a transportable drag hose or underground pipelines may be beneficial when compared with traditional tanker systems. A typical separation scenario involving a decanting centrifuge may reduce the transport distance by 61–78% as compared with a scenario without separation. Overall, evaluations show that it is possible to combine the normally conflicting goals of maintaining efficient application systems, in terms of low labor input and high capacity to satisfy workability constraints, while at the same time complying with environmental constraints in terms of reduced ammonia and odor emissions.

**Keywords:** manure-handling systems, labor requirement, capacity, time-motion study, manure application

## 1. Introduction

Among the challenges faced by livestock producers is the design and implementation of effective and sustainable manure-handling systems (Burton, 1997; Araji, 2001; Rom and Sørensen, 2001). The operational capability of the applied technology is becoming more important as an integral part of manure-handling (Brundin and Rodhe, 1994; Huijsmans and de Mol, 1999). The farm manager needs detailed knowledge of operational and logistical capabilities when implementing application technologies while at the same time complying with environmental regulations.

A tendency toward the specialization of animal husbandry in Denmark has led to geographic concentration of production systems in certain areas (DAC, 2002). This concentration of production on large farms has long caused problems in the storage, handling, and spreading of manure. Further-

more, crop production farms are often geographically separated from mixed arable and livestock farms, making it difficult and costly to export the surplus manure from one farm to another.

The shift in application methods has been very rapid in recent years in Denmark. In 1999 approximately 45–50% of the manure was applied by use of trailing hoses, 45–50% by broad spreading, and 1–3% by injection methods (Andersen et al., 1999), and by 2001 approximately 75% was applied by use of trailing hoses, 15% by broad spreading and 10% by injection (Andersen and Hald, 2001). The trailing hose method involves the distribution of the slurry through a line of separate tubes (20 or 40 cm apart) placed in bands on the ground. This method can be used both on growing crops and on bare soil (Sørensen, 1993). On fallow land, application can be followed immediately by incorporation into the soil with a plough or some sort of harrow (stubble cultivator). However, the ever-increasing demand for more efficient utilization of the nutrients in the manure has encouraged the use of various injection methods. Unlike earlier deep/closed slit types, current injection methods are predominantly of the shallow injection type, where the slits are left open and are only covered when followed by a harrow (Huisman et al., 1998).

Normally, the best utilization of the slurry will be achieved by application in early spring before sowing or by application to a growing crop. The use of heavy slurry tankers and more sophisticated and possibly laborious application methods such as injection may involve an increased risk of soil compaction (Håkansson and Danfors, 1998). In addition, because the spring months represent an intensive work period for other operations, the application of slurry may end up causing a negative timeliness effect. The use of umbilical systems, where the manure is conveyed directly to the field, might be preferred. In this system the liquid manure is fed through a transport hose to a self-propelled in-field applicator with trailing hoses, eliminating the transport with tankers. The transport hose is fed directly from the store or from a buffer tank.

The aim of this study was to develop models and procedures suitable for carrying out an operational evaluation of specific slurry application techniques and distribution configurations in terms of labor input, machine capacity, and logistics. The application methods were to include injection and surface application in terms of trailing hoses aimed at maximizing nutrient utilization. The hypothesis was whether it is possible to maintain a high-capacity system while at the same time complying with environmental constraints such as reduced ammonia emissions (e.g., Søgaard et al., 2002). In order to reduce nitrogen leaching and improve nutrient utilization, it is important to regulate the number of animal units per hectare (Hasler et al., 1999) but, conversely, the tightening of such harmonization demands in terms of regulatory required adjoining land for manure application will affect the resources needed for transport. This study combines selected on-farm time studies with supplementary data from various sources for model development, and uses case-based scenarios for specific manure system evaluations.

## 2. Methodology

### 2.1. Application evaluation

The quantity of animal manure produced, together with the type of manure, including separated fractions, determines the composition and quantity of nutrients available. Normally a maximum rate of N or P will be the determining factor for setting the application rate per hectare and thus the necessary size of the spreading area. Furthermore, the average transport distance is determined by geographical position and shape of the adjoining land suitable for slurry application. The overall manure application process, taking into account the dosage and transport distance, may be compared with a traditional production process, with the output being the performed application work. As for traditional production processes, the manure application may be planned and executed

for maximum performance. This planning requires detailed analyses and modeling efforts with regard to labor and machine capability, especially as related to the transport distance.

## 2.2. Model description

### 2.2.1. On-farm analyses

The manure-handling activities, as part of the work operations on the farm, were investigated by the use of detailed work studies producing basic performance data (time required, machine performance, etc.). These data were used in two ways: (1) in a diagnostic way to determine the “current state” of the manure-handling system, or (2) in a prognostic way to predict the state of the manure-handling system given operational variables including machinery size, transport distance, dosage, etc. The latter data application involves the use of work models (labor requirement/machine capacity as a function of machinery size, dosage, etc.) using the data for work elements as building blocks for such models (e.g., Auernhammer, 1976; Nielsen and Sørensen, 1993; Achten, 1997). The work models are then aggregated to different levels, such as machine level, crop level, farm level, etc. (see fig. 1).

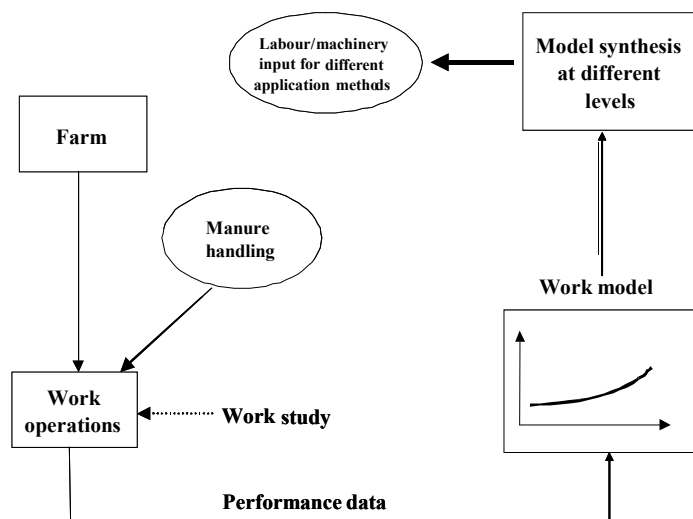


Figure 1. Methods of analyzing and modeling farm operations.

In general, the analysis of farm operations involves a number of entities, such as job, operation, task, work element, etc., which have to be examined in order to assess the operational efficiency of labor and machinery activities on the farm (Witney, 1995; Goense & Blaauw, 1996). Table 1 explains the different elements as related to the manure-handling process. The entity “work element” functions as the basis for building models capable of estimating the labor requirement on different aggregated levels.

**Table 1.** Definition of work components

Designation	Work operations – field
Work element	Smallest activity unit identified and involves a sequence of working movements. Example: “prepare for loading of slurry tanker”
Operation	Sequence of work elements*. Example: “spreading slurry on the field”
Task	Sequence of operations. Example: “loading”, “transport” and “spreading”
Job	A combination of tasks. Example: “slurry application”

\*An operation is “a technical coherent combination of treatments by which at a certain time a characteristic change of condition of an object (e.g., a field, an equipment, a crop) is observed, realized or prevented” (van Elderen, 1977).

Detailed on-farm work studies were carried out on 56 preselected commercial farms during times of slurry application. On each farm, the slurry handling was performed using modern state-of-the-art handling techniques (table 2). The whole sequence of manure-handling operations was monitored in terms of loading, transport, and spreading on the field. The labor content of each work element was measured, together with the acquisition of information on the machine specifications, shape and size of fields, etc.

**Table 2.** Characteristics of the application systems involved in the investigation

Application technique	No. of farm systems	Payload (m <sup>3</sup> )	Working width (m)	Dosage (t ha <sup>-1</sup> )
Self-propelled tanker:				
- black soil injectors	5	13.4–20.2	5.9–7.5	24.4–34.2
- grassland injectors	7	13.4–20.3	7.9–8.1	10.3–30.2
Tractor-pulled tanker:				
- fallow land injectors	10	10.3–22.7	5.8–7.2	16.3–62.9
- grassland injectors	10	15.3–20.3	6.0–10.0	23.0–29.5
Tractor-pulled tanker:				
- trailing hoses	6	19.5–25.2	15.2–24.0	27.0–62.5
Umbilical systems:				
- trailing hoses	10	–	18.0–24.0	27.0–55.0

The numbers for the payload, working width, and dosage are min/max values.

### 2.2.2. Labor and machine input

The collected and analyzed data, together with the observed work methods, form the basis for the development of normative models for estimating labor input and machine capacity for specific application techniques. Work models for the operations of loading, transport, and spreading have been developed (see table 3 and Equation (1)) based on the principles outlined in Sørensen (1993).

**Table 3.** Work models for tanker systems

Operations	Work model	Definitions
Loading at the store	$L = \left(\frac{u}{r}\right) \times \left( \left( \frac{r \times 60}{d} \right) + m \right) (1+q)$	$L, T, T_1, P, S$ are the labor requirement, $\text{min ha}^{-1}$ $u$ is the dosage, $\text{t ha}^{-1}$ $r$ is the tanker load, $\text{t}$ $d$ is the pump capacity, $\text{t h}^{-1}$ $m$ is the preparation for loading, $\text{min per load}$
Transport from store to field	$T = \left(\frac{u}{r}\right) \times \left( \frac{t \times 0.12}{v} \right) \times (1+q)$	$q$ is the rest allowances $t$ is the one-way transport distance, $\text{m}$ $v$ is the transport velocity, $\text{km h}^{-1}$
Spreading on the field: Transport on field	$T_1 = \left(\frac{u}{r}\right) \times \left( \frac{t_1 \times 0.12}{v_1} \right) \times (1+q)$	$t_1$ is the one-way transport distance on field, $\text{m}^*$ $v_1$ is the transport velocity on field, $\text{km h}^{-1}$
Preparation in field	$P = \left(\frac{u}{r}\right) \times m_1 \times (1+q)$	$m_1$ is the preparation for unloading, $\text{min per load}$ $h$ is the area, $\text{ha}$
Spreading	$S = \frac{\left( \left( \frac{h \times u}{d_1} \right) + \frac{p \times b}{e} + k + (h \times s) \right)}{h} \times (1+q)$	$d_1$ is the unloading capacity, $\text{t min}^{-1}$ $p$ is the turning time, $\text{min per turn}^{\S}$ $b$ is the width of field, $\text{m}$ $e$ is the effective working width, $\text{m}$ $k$ is the turnings on headland, $\text{min per field}^{\S}$ $s$ is adjustments, control, etc., $\text{min ha}^{-1}$

\*The estimation of the transport distance,  $t_1$ , in the field is arbitrary by assuming that each load, on average, will be transported a distance that runs from the centroid lengthwise down the field to the end of the field and from there to the corner of the field. Nielsen and Sørensen (1993) present models for estimating  $t_1$  for different field shapes and field sizes.

<sup>§</sup>  $p$  is the turnings while driving on the mainland of the field (back and forth in passings) and  $k$  is the turnings while driving on the headland of the field

For the umbilical system, a modified model approach was necessary:

$$U = \frac{\left( \frac{h \times u}{d_1} + (h \times s) + (m_2 \times a_1) + (m_3 \times a_2) + ((m_4 + m_5) \times (t + a_3 \times y_1)) \right)}{h} \times (1+q) \quad (1)$$

where  $U$  is the labor requirement ( $\text{min ha}^{-1}$ ),  $m_2$  is the time for setting up the pump (min),  $a_1$  is the number of pump mountings,  $m_3$  is the timer for preparing and finishing the applicator for operation (min),  $a_2$  is the number of preparations,  $m_4$  is the time for unwinding the hose ( $\text{min m}^{-1}$ ),  $m_5$  is the time for rolling up the hose ( $\text{min m}^{-1}$ ),  $t$  is the distance between the storage and field border (m),  $a_3$  is the number of field changes, and  $y_1$  is the distance between neighboring fields (m). The remaining model parameters are explained in table 3.

### 2.2.3. Transport and distribution modeling

The transport distance is the decisive factor for the transport costs assigned to the handling of biomaterials (Hansen and Østergaard, 1991; Nilsson, 1995; Sonesson, 1996). The form, size, and position of the adjoining land relative to the position of the storage determine the transport distance (Keller et al., 1971). The perfect positioning of the adjoining land in terms of shortest transport distance demands that the land form a circular area around the storage depot. However, as that is seldom the case, the implications of irregular adjoining lands must be accounted for in the models. The following generic modeling approach is applied to evaluate the transport effort necessary for

the distribution of slurry to fields allocated in an arbitrary manner with relation to the position of the storage. Conceptually, figure 2 shows the adjoining land and the storage. The transport work is defined as:

$$T(i, j) = f_{i,j} \times F(l_i^1, l_i^2, x_j, y_j) \quad (2)$$

where  $T(i, j)$  is transport work (t km),  $f_{i,j}$  is the mass flow (t),  $l_i^1, l_i^2$  are the coordinates for the store location,  $x_j, y_j$  are the coordinates for the distribution locality, and  $F$  is a distance function (e.g., rectangular or Euclidian).

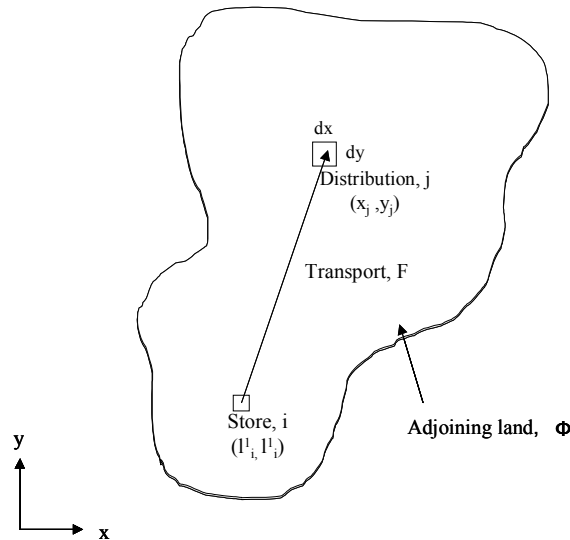


Figure 2. Conceptual outline of adjoining land with storage location and distribution.

The model may be used to optimize the position of the storage relative to the distribution sites. It may involve separate distribution sites, like the transportation of slurry from biogas plants to individual farm storages, or it may involve distribution sites evenly scattered over an area as outlined in figure 2. In the latter case,  $f_{i,j}$  equals,  $w$ , as denoting the dosage in  $\text{t ha}^{-1}$ . By expressing the adjoining land of a certain shape and size by,  $\phi$ , the total transport work,  $T$ , is expressed as a planar integral:

$$T = \iint_{\phi} w \times F(l^1, l^2, x, y) dx dy \quad (3)$$

where  $(l^1, l^2)$  is the fixed storage location. The total transport work may, in principle, be estimated for arbitrary forms of the adjoining land and positioning of the storage. However, the calculus is laborious for irregular forms of the adjoining land and may be eased by assuming  $\phi$  to be circular with the storage located at a certain distance from the center of the circle. Distribution is carried out throughout the whole area with an even dosage.

$$T = 2 \times w \times \int_0^R \int_0^{\pi} \sqrt{(E + r \cos \Theta)^2 + (r \sin \Theta)^2} r dr d\Theta \quad (4)$$

where  $T$  is the transport efforts (t km),  $w$  is the dosage (t ha<sup>-1</sup>),  $R$  is the radius of the circular adjoining land (m),  $E$  is the distance from the storage location to the circle center (m), and  $\Theta$  is a circular angle counter. By setting  $E' = E/R$  and  $r' = r/R$  the following is obtained (see Appendix):

$$T = 2 \times w \times R^3 \times \pi \times I(E') \quad (5)$$

For  $E' = 0$ , e.g., the storage is located at the center of the circle, then  $T = 2/3 \times w \times \pi \times R^3$ , where  $w \times \pi \times R^2$  expresses the total amount of manure being distributed on the adjoining land with an average transport distance of  $2/3 \times R$ . For  $E' \neq 0$ , e.g., the storage is located at a certain distance from the center, an integration of Equation (A3) must be performed. It can be shown that moving the storage to the perimeter of the circle increases the transport distance by 70% (fig. 3).

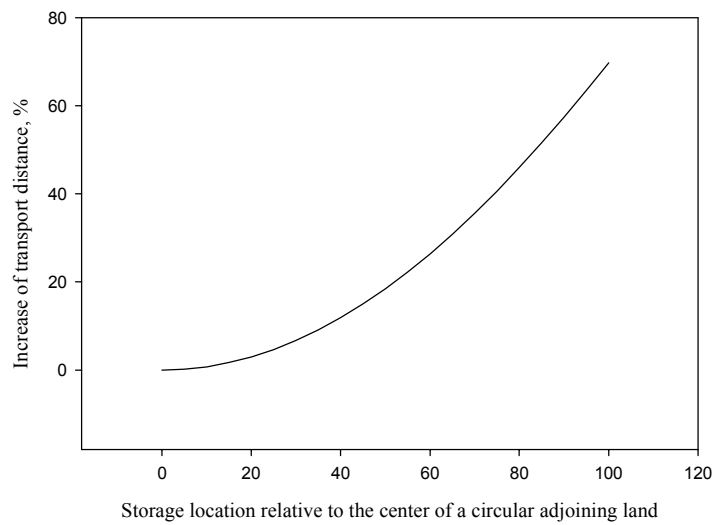


Figure 3. Increased transport distance as a function of storage position.

#### 2.2.4. Multiple manure-receiving localities

Often the situation will require that parts of the total manure production are transported off the farm to be stored and spread on a cooperating farm. Assuming a certain distance from the primary store to the secondary store, the transport work may be estimated based on the Equation (3):

$$T = 2 \times w_1 \times \pi \times R_1^3 I(E_1') + 2 \times w_2 \times \pi \times R_2^3 I(E_2') + M \times \eta \times d \quad (6)$$

where  $T$  is the total transport work (t km),  $w_1$  is the dosage for the primary recipient (t ha<sup>-1</sup>),  $R_1$  is the radius in the circular adjoining land for the primary recipient (m),  $E_1'$  is the distance from the primary store location to the circle center,  $w_2$  is the dosage for the secondary recipient (t ha<sup>-1</sup>),  $R_2$  is the radius of the circular adjoining land for the secondary recipient (m),  $E_2'$  is the distance from the secondary storage location to the circle center,  $M$  is the total amount of manure produced (t),  $\eta$  is the ratio of the produced manure transported to the secondary recipient (t), and  $d$  is the distance from the primary storage to the secondary storage.

#### 2.2.5. Prescribed adjoining lands

Variants in the form of the adjoining lands may be prescribed in terms of average transport distances. The radius *in meters* may be estimated as  $\sqrt{(c \times A \times 10000 / \pi)}$ , where  $c$  is a correction factor depending on the form of the adjoining land,  $c = 1$  for circular land,  $c = 2$  for semicircular land,  $c = 4$  for quarter-circular land,  $A$  is the area of the adjoining land. The adjoining lands and their characteristics form the basis for evaluating the influence of the transport distance on operational performance. The average transport distance is estimated as  $\frac{2}{3}$  of the estimated radius.

#### 2.2.4. Workability constraints

The potential number of operating hours for slurry application was derived as a function of meteorological variables and specific workability criteria. Hansen and Østergård (1991) give the following criteria in terms of temperature limits and precipitation limits (table 4). Strict criteria were necessary because of highly regulatory requirements for nitrogen utilization.

**Table 4.** Workability criteria for slurry application in the period March 1 to June 15

Soil type	Clay soil		Sandy soil	
	03-01 to 04-20	04-20 to 06-15	03-01 to 04-20	04-20 to 06-15
Application period				
Precipitation of the current day, mm	<1	<1	<3	<3
Temperature of the current day, °C	>1	<18	>1	<18
Sunshine hours of the current day, hours	no request	<6	no request	<6
Precipitation for the last 7 days, mm	<30	<20	<40	<40
Precipitation for the last 3 days, mm	<15	<10	<20	<20
Precipitation for the last 2 days, mm	<8	<7	<10	<15
Precipitation for the last day, mm	<3	<3	<6	<7

These criteria were used to determine suitable work days from recorded meteorological data at the location Askov (55°28' N, 09°06' E) for the weather years 1961–90.

### 3. Results and discussion

#### 3.1. Tasks and operations

On average, the observed labor requirements for the individual operations involved with the tasks of loading, transport, and in-field spreading were generally about 23–54% lower for the self-propelled tanker than for the tractor-pulled tanker (table 5). This indicates increased maneuverability by the self-propelled tanker and better in-field reliability.

Previous investigations into the labor content of selected work elements of manure application found a value of 0.50 min per turning for tractor-pulled tankers ( $p$ ) and a value of 2.00 min for preparing and finishing loading ( $m$ ) at the storage (Huijsman and de Mol, 1999). This is similar to the current findings, which indicates relatively consistent values for these elements across different usage scenarios.



**Table 5.** Observed labor requirements and model parameter estimation

Task		Units	Application technique	
Loading	Operation		Self-propelled tanker	Tractor-pulled tanker
	Access for loading	min/load	0.44 ± 0.22 (49)	0.76 ± 0.48 (61)
	Prepare for loading	min/load	0.25 ± 0.11 (56)	0.28 ± 0.24 (58)
	Finish loading	min/load	0.30 ± 0.08 (56)	0.27 ± 0.18 (50)
	Exit loading	min/load	0.50 ± 0.34 (50)	0.62 ± 0.35 (62)
	Total ( <i>m</i> )	min/load	1.49 ± 0.43	1.93 ± 0.67
Transport	Road transport ( <i>v</i> )	km h <sup>-1</sup>	14.5 ± 3.2 (43)	25.9 ± 6.3 (15)
	In-field transport ( <i>v</i> <sub>1</sub> )	km h <sup>-1</sup>	16.4 ± 2.4 (10)	16.4 ± 2.4 (10)
Spreading	Prepare/finish unloading ( <i>m</i> <sub>1</sub> )	min/load	0.36 ± 0.08 (36)	0.59 ± 0.21 (36)
	Adjustments, stops ( <i>s</i> )*	min ha <sup>-1</sup>	1.35 ± 1.21 (21)	2.93 ± 1.85 (45)
	Turning time:			
	180°	min/turn	0.26 ± 0.09 (89) (55%) <sup>†</sup>	0.31 ± 0.11 (118) (35%) <sup>†</sup>
	180°, 1 reverse	min/turn	0.34 ± 0.07 (51) (38%)	0.50 ± 0.14 (136) (53%)
	180°, 2 reverse	min/turn	0.54 ± 0.14 (15) (7%)	0.74 ± 0.15 (17) (12%)
	90°, 1 reverse	min/turn	0.22 ± 0.07 (2)	0.58 ± 0.18 (7)
	Prescribed turning ( <i>p</i> )	min/turn	0.31 ± 0.08	0.47 ± 0.13
	Prescribed turning ( <i>k</i> ) <sup>‡</sup>	min/field	2.24 ± 0.20	4.32 ± 0.45
	Effective working width ( <i>e</i> ):	% of		
	fallow soil	nominal,	98.9 ± 1.1 (9)	100.2 ± 1.7 (5)
	grassland	m	99.7 ± 0.7 (9)	98.8 ± 1.0 (6)

Data are means ± SD (no. of observations).

\**s* is estimated as an average for all loads spread on the field.

<sup>†</sup>The percentages denote the observed distribution of the various types of turning, which are used to weight the prescribed turning time.

<sup>‡</sup>Prescribed turning on headlands involves three passes for each headland and two “180° 1 reverse” and two “90° 1 reverse” turns. There is a significant difference for the *m*, *m*<sub>1</sub>, *p*, and *k* parameters (*P*<0.05).

For the umbilical system, the operations involved with setting up the system and preparing for operation require a considerably labor input. (Table 6). In particular, work with the hose reel and the unwinding and rolling up of the main mobile hose is time-consuming. These work activities are omitted in cases where the applicator has its drag hose connected to in-field hydrants.

**Table 6.** Observed labor requirement for operation of an umbilical system

Task		Units	Application technique
Loading	Operation		Umbilical system
	Adjustments, stops, etc. ( <i>s</i> )	min ha <sup>-1</sup>	0.56 ± 0.23 (4)
	Setting up the pump ( <i>m</i> <sub>2</sub> )	min	17.08 ± 9.98 (10)
	Prepare the applicator ( <i>m</i> <sub>3</sub> )	min	5.09 ± 2.62 (10)
	Unwinding hose ( <i>m</i> <sub>4</sub> )	min 100 m <sup>-1</sup>	4.79 ± 2.47 (10)
	Roll up of hose ( <i>m</i> <sub>5</sub> )	min 100 m <sup>-1</sup>	7.41 ± 3.26 (10)

Data are means ± SD (no. of observations).

### 3.2. Total labor requirement and operational capability

The total labor requirement involved in slurry application was dependent on the technology used, the measured work elements, the technical specifications of the pumps, tankers, transport distance, and dosage. The developed models enable the estimation of the total labor requirement by allocating the time requirements to the specific work elements, operations, tasks, and jobs. In figure 4, the standardized labor requirement for the tasks of loading, transport, and spreading, as well as the overall system capacity, was estimated for specific application systems. The labor requirement

varied from 16 to 35 min ha<sup>-1</sup> (the umbilical system versus the tractor-pulled tanker with injector). The use of shallow injection as compared with surface application increased the labor requirement but decreased the capacity by 7–20% depending on whether it was a self-propelled or a tractor-pulled tanker. Comparisons also show that shallow type injectors with working widths of 6–8 m have considerably greater capacity (35–40%) than the deep/closed type with working widths of 2–3 m (Sørensen, 1993).

Clearly the most significant decrease in labor requirement is experienced in connection with the umbilical system, where the system with the in-field hydrants may lower the labor input by 42–57% and increase the capacity by 73–116%.

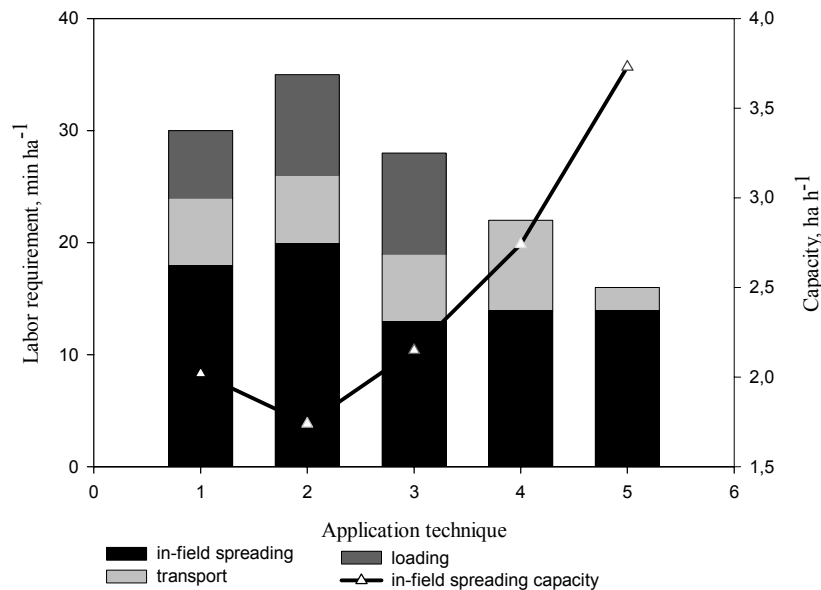


Figure 4. Comparison of different application techniques for a transport distance of 500 m and rate of 25 t ha<sup>-1</sup>. Supplemental default values are based on average measured values from the on-farm studies: 1, self-propelled tanker with injector (loading capacity 500 m<sup>3</sup> h<sup>-1</sup>; emptying capacity 220 m<sup>3</sup> h<sup>-1</sup>; working width 7 m; payload 16 t); 2, tractor-pulled tanker with injector (loading capacity 300 m<sup>3</sup> h<sup>-1</sup>; emptying capacity 160 m<sup>3</sup> h<sup>-1</sup>; working width 7 m; payload 16 t); 3, tractor-pulled tanker with trailing hoses (loading capacity 300 m<sup>3</sup> h<sup>-1</sup>; emptying capacity 360 m<sup>3</sup> h<sup>-1</sup>; working width 24 m; payload 16 t); 4, umbilical system with mobile hose (pump capacity, 120 m<sup>3</sup> h<sup>-1</sup>; working width 24 m); 5, umbilical system coupled to in-field hydrants (pump capacity, 120 m<sup>3</sup> h<sup>-1</sup>; working width 24 m).

For the umbilical system, the most laborious work elements are the setting up and preparation of the hose system for in-field operation. Comparing a situation where the application field is divided into two separate fields requiring the hose system to be prepared twice instead of once, the application capacity is reduced by 23%. In the case of an umbilical system with in-field hydrants, the same scenario only reduces the capacity by 4%. Brundin and Rodhe (1994) also emphasize the difficulty of moving a modified irrigator with trailing hoses between locations of spreading, which is comparable to the current umbilical system in terms of installation and preparation.

The results indicate that it is possible to maintain highly efficient application systems such as shallow injection on fallow land or grassland and umbilical systems with trailing hoses in growing crops, while at the same time meeting regulatory utilization and environmental requirements.

### 3.3. Influences on the operational capability

The independent variables in the work models (table 2) influence the total labor requirement to varying degrees. Figure 5 shows as an example the detailed analysis of factors influencing the

capacity of the tractor-pulled tanker with an injector as a function of selected factors varied within a range of  $\pm 50\%$ .

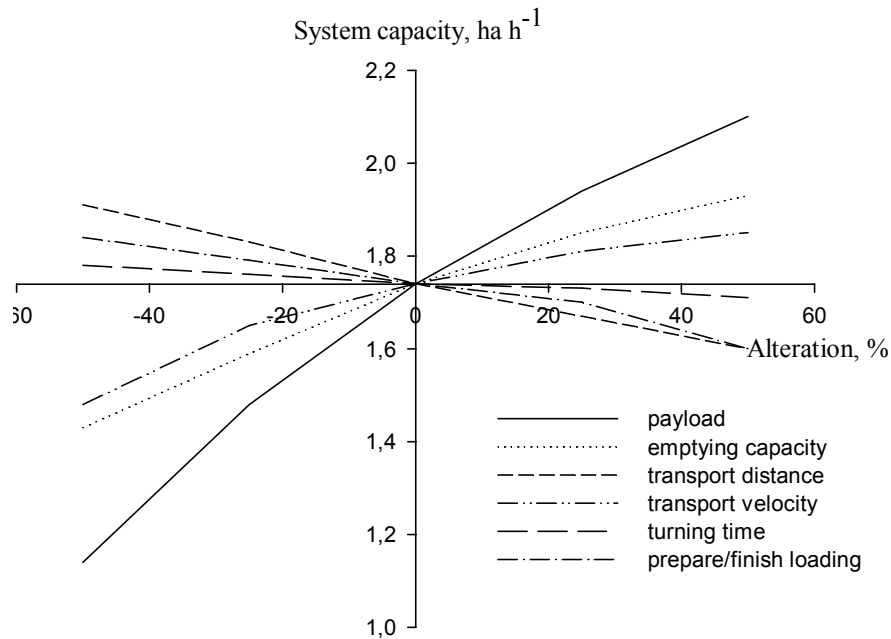


Figure 5. Influences on the system capacity for the tractor-pulled injector. The reference scenario for all parameters is a payload of 16 t, emptying capacity of  $2666 \text{ l min}^{-1}$ , dosage of  $25 \text{ t ha}^{-1}$ , transport distance of 500 m, transport velocity of  $18 \text{ km h}^{-1}$ , and the remaining parameters depicted in table 2. The reference capacity is  $1.74 \text{ ha h}^{-1}$ .

The most significant influence is the payload. By changing the payload  $\pm 50\%$ , the capacity is either reduced by 34.5% or increased by 20.7%. The emptying capacity is the second most influential factor, where changing the base value by  $\pm 50\%$  either reduces the capacity by 17.8% or increases it by 10.9%. Other factors, in descending order of influence, include the transport distance, transport velocity, turning time, and preparation and finishing of loading. Similar results were found for the self-propelled tanker.

### 3.4. Logistics and distribution strategies

Model estimations show that transport often constitutes the major part of the total labor requirement for slurry application. For example, in the case of the self-propelled injector, an extension of the transport distance from 500 to 2000 m and using the prerequisites from figure 2, the transport work amounts to 20% or 50% of the total, respectively. Environmental regulations require that the manure-receiving land and the manure production area need to be harmonized in terms of livestock units (LU) per hectare (ME, 1998). The threshold is  $1.4 \text{ LU ha}^{-1}$  for pigs and  $1.7 \text{ LU ha}^{-1}$  for cattle. In this respect, the average transport distance increases with the amount of manure produced. Assuming a quarter-circle as the shape of the adjoining land, it is estimated that an increase from 2000 to 6000 t increases the average distance from about 650 to about 1100 m.

Little information is available on the actual shape of the adjoining land in Danish agriculture, but Jacobsen et al. (2002) concludes, based on interviews on study farms, that the distance for slurry application was, on average, twice as large as the ideal circle-shaped adjoining land area. Referring to the transport models in table 2, this finding suggests that the shape used for modeling should be a quarter-circle. Swedish investigations seem to support this assumption (Brundin and Rohde, 1990).

By using a quarter-circle as the shape of the adjoining land, the average transport distance is estimated for various different scenarios involving amounts of manure and harmonization demands in terms of regulatory determined adjoining land (figure 6).

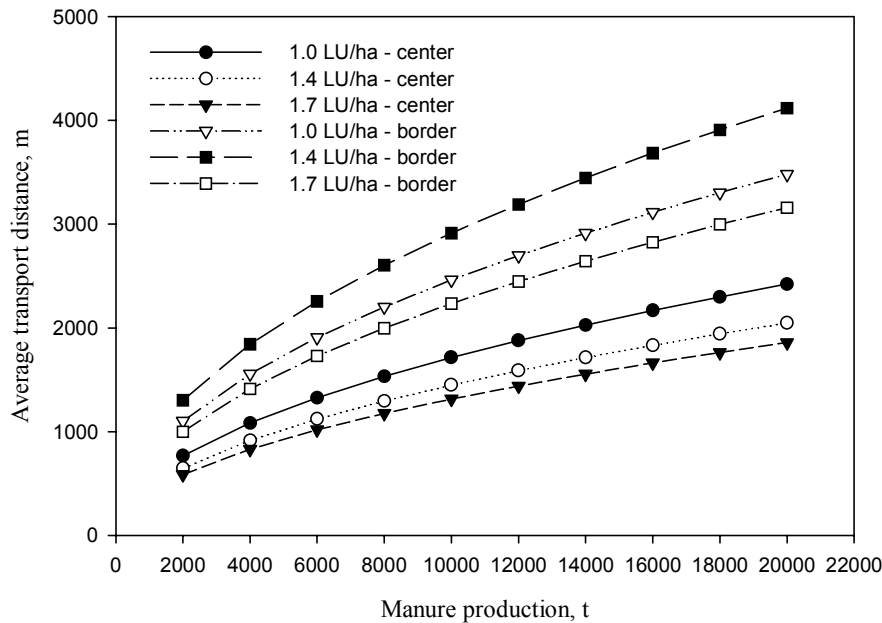


Figure 6. Average distance as a function of manure production. The shape of the adjoining land is a quarter-circle. The dosage amounts are 19.3, 27.0, and 32.8 t ha<sup>-1</sup> for the selected harmonization requirements. Center and border refer to two alternative positions for the storage, either in the center of the circle or at the periphery.

The average distance increases by 30% when the harmonization requirement goes from 1.7 LU ha<sup>-1</sup> to 1.0 LU ha<sup>-1</sup>. As the transport model (figure 3) predicts, the distance increases by 70% when the storage is placed at the border of the quarter-circle instead of in the center. The average transport distance is more influenced by the quantity of manure handled in the case of the storage placed at the periphery of the circle than in the case of center positioning. Hasler et al. (1999) reports that farmers tend to apply an excessive amount of manure on fields near the storage location in order to reduce transport costs, but by doing so they are not able to achieve optimal utilization of the manure nutrients.

To apply the slurry within the limits imposed by suitable working days, the application system requires sufficient capacity (table 7).

Table 7. Total labor requirement as a function of manure production and tanker size

Amount, t	Payload*, t	Harmonization area†, ha	Distance, m	Time requirement, hours
2000	12	74	647	48
4000	15	148	916	109
6000	12	222	1121	214
6000	15	222	1121	174
8000	18	296	1295	217
8000	20	296	1295	203
10000	20	370	1448	264
10000	22	370	1448	251
12000	22	444	1586	311
12000	24	444	1586	295

\*Tractor-pulled tanker equipped with a shallow injector. †1.4 LU ha<sup>-1</sup>.

The potential number of days suitable for slurry application was estimated yearly over the 30-year period of 1961–90 (fig. 7). In 1974, sandy soil allowed 56 days to be available for slurry application, while clay soil only allowed 10 days in 1970. On average, 23.3 d/yr were available for slurry application on clay soil and 34.9 d/yr were available on sandy soil. By assuming a working day of 8 hours, the corresponding number of hours was 186 and 280, respectively.

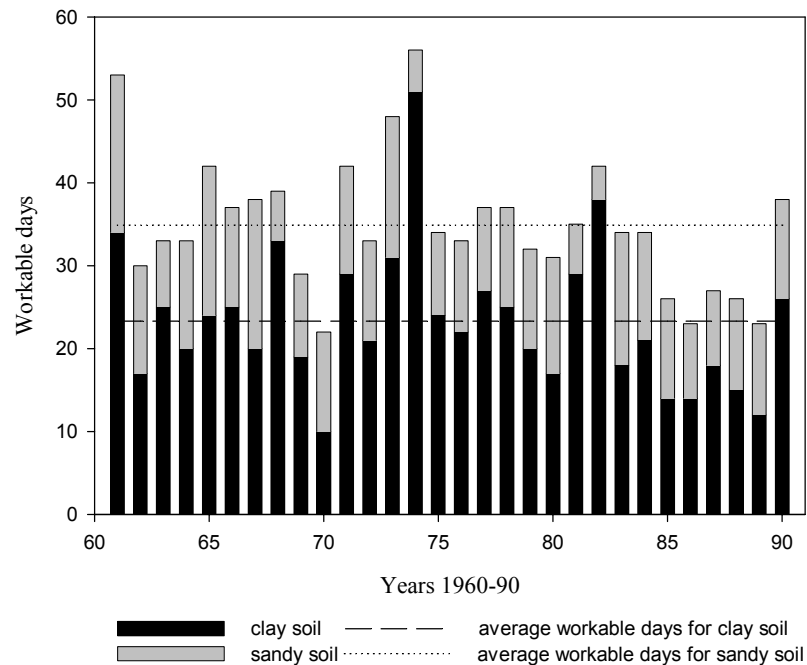


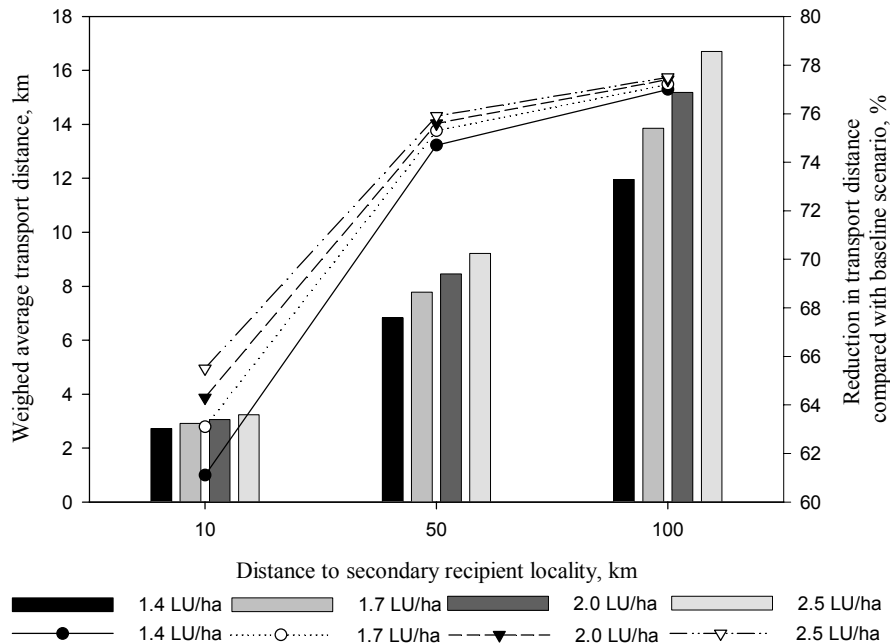
Figure 7. Workable days for manure application during the years of 1961–90 and the period March 1 to June 15. The total height of the columns indicates the number of working days for sandy soil while the black part of the columns indicates the number of working days for clay soil.

These results may be compared to the time requirements in table 7. For example, the difference between sandy and clay soil could reduce the payload requirement by 20–35% because more hours are available for sandy soil. For yearly amounts of manure above 10 000 t, multiple tankers are required. Overall, the quantification of workable days is important in order to select and size needed equipment.

### 3.5. Separation of slurry and transport strategies

Liquid and solid separation of slurry provides a number of advantages, depending on the type of separation technology used. These include lower costs of storage, transport, and application of slurry, as well as better utilization of the nutrients in the field (Pain and Hephherd, 1980; Møller et al., 2000). Jacobsen et al. (2002) divided separation equipment into two categories; namely, high-technology systems and low-technology systems. High-technology separation produces a range of nutrient-rich fractions and a watery fraction, with the result that only 20% of the initial volume of the slurry has to be stored and applied to the field using traditional slurry applicators. However, this system is currently not sufficiently developed and documented. A low-technology separation method such as the decanting centrifuge is well documented and may be used to reduce the transport efforts of specific phosphorus from areas with a high concentration of animal husbandry to recipient areas specializing in crop production. At the same time, the application rate can be increased near the farm without incurring the risk of over-applying nutrients. A typical transport

scenario involves: (1) that the liquid fraction from the decanting separation be applied following the N requirements, (2) that a certain amount of the separated solid fraction be applied following the P requirements with in the harmonization area supplemental to the liquid fraction, and (3) that the surplus solid fraction be transported off the farm to a secondary recipient location. Figure 8 shows the transport distances for decanting fractions as a function of the distance to “manure-free” areas receptive to manure application and as a function of varying harmonization demands in terms of LU  $\text{ha}^{-1}$ . The shape of the adjoining land is assumed to be a quarter circle with an area corresponding to the respective harmonization area. Equation (6) is used for the estimations.



*Figure 8.* Distance for total transport of manure for application on primary farm land, transport to secondary recipient land, and subsequent application (bar values). Default values: 1000 LU, equaling 20 000 t of slurry per year. The dosage for the liquid fraction and the solid fraction from the separation is 180 kg N per ha (utilized 145 kg N per ha) equaling 37 t  $\text{ha}^{-1}$  and 21 kg P  $\text{ha}^{-1}$  equaling 3 t  $\text{ha}^{-1}$ , respectively. The reduction of the transport distance is related to a baseline scenario involving no separation and application of raw slurry with a dosage of 21 kg P  $\text{ha}^{-1}$  equaling 14 t  $\text{ha}^{-1}$  (line values).

For shorter distances to secondary locations, the average transport distance is only dependent to a small degree on the harmonization demands. The dependency grows when this distance is increased. The transport distance and work is reduced by 61–78% compared to the baseline scenario.

#### 4. Conclusion

Manure handling capacity was affected by a number of activities and process factors, such as machine specification, size and shape of the adjoining land used for application of the manure, etc. In order to predict and evaluate the operational performance of specific systems, models for labor input and machine input, including submodels for transport distance, were developed. The normative models enabled detailed derivation of work requirements as the input for model synthesis at different aggregation levels, such as loading, transport, and spreading. Specifically, the transport

models estimate average transport distances given predimensioned adjoining lands. Also, the principles for estimating the number of potential operating hours were derived.

Modern types of application technology, like shallow injectors and umbilical systems, are capable of maintaining high capacity while fulfilling environmental requirements in terms of reduced ammonia emission, reduced risk of soil compaction, etc. The capability of shallow injectors may be compared with more traditional application systems such as the trailing hose system. The labor requirement varied from 16 to 35 min ha<sup>-1</sup> (the umbilical system versus the tractor-pulled tanker with injector). The use of shallow injection as compared to surface application either increased the labor requirement or decreased the capacity by 7–20% depending on whether it was a self-propelled or a tractor-pulled tanker. The most significant influence was from the payload, while other factors, in descending order of influence, include the transport distance, transport velocity, turning time, and preparing and finishing loading. The use of umbilical systems may lower the labor input by 42–57% and increase the capacity by 73–116% in its most efficient configuration.

Evidence suggests that the shape used for capturing and modeling the adjoining land for spreading should be a quarter-circle. The average distance increases by 30% for that shape of adjoining land when the harmonization requirement changes from 1.7 LU ha<sup>-1</sup> to 1.0 LU ha<sup>-1</sup>. Dislocation of the storage in relation to the circle center may increase the transport work by 70%.

Workability is an important factor in determining the seasonal capability of manure-handling machinery. On average, 23.3 days per year are available for slurry application on clay soil and 34.9 days are available on sandy soil. By assuming a working day of 8 hours, the corresponding number of hours is 186 and 280 per year for the period March 1 to June 15.

In the case of a typical separation scenario the average transport distance is not greatly dependent on the harmonization demands when distances to secondary localities for the application of the solid fraction are small, but the dependency increases when this distance is increased. The transport distance and work is reduced by 61–78% as compared with the baseline scenario involving no separation.

The developed model is shown to be able to evaluate the operational performance of manure-handling machinery for different farm scenarios and application scenarios. In addition, the results from using the model may be further extended to serve as input for the estimation of economic indicators.

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## Nomenclature

The following list denotes the mathematical symbols and notations used. The units associated with the symbols are given in square brackets, if relevant.

$L$	labor requirement [min ha <sup>-1</sup> ]
$u$	dosage [t ha <sup>-1</sup> ]
$r$	tanker load [t]
$d$	pump capacity [t h <sup>-1</sup> ]
$M$	preparation for loading [min per load]
$q$	rest allowances [min ha <sup>-1</sup> ]
$T$	labor requirement [min ha <sup>-1</sup> ]
$U$	dosage [t ha <sup>-1</sup> ]
$R$	tanker load [t]
$t$	transport distance [m]
$v$	transport velocity [km h <sup>-1</sup> ]
$T_1$	labor requirement [min ha <sup>-1</sup> ]
$t_1$	transport distance on field [m]
$v_1$	transport velocity on field [km h <sup>-1</sup> ]
$P$	labor requirement [min ha <sup>-1</sup> ]
$m_1$	preparation when starting unloading in field [min per load]
$S$	labor requirement [min ha <sup>-1</sup> ]
$h$	area [ha]
$d_1$	unloading capacity [l min <sup>-1</sup> ]
$p$	turning time [min per turn]
$b$	width of field [m]
$e$	effective working width [m]
$k$	turnings on treatment of headland [min per field]
$s$	crop and soil stops, adjustments, tending of machine, etc., [min ha <sup>-1</sup> ]
$m_2$	time for setting up the pump [min]
$a_1$	number of pump mountings
$m_3$	timer for preparing the applicator for operation [min]
$a_2$	number of preparations
$m_4$	time for unwinding the hose [min m <sup>-1</sup> ]
$m_5$	time for roll up the hose [min m <sup>-1</sup> ]
$t$	distance between storage and field border [m]
$a_4$	number of shiftings between fields
$y_1$	distance between neighboring fields [m]
$T(i, j)$	transport work [t*km]
$d_{i,j}$	distance from the storage location, $i$ , to the distribution locality, $j$ [km]
$f_{i,j}$	corresponding mass flow [t]
$T$	transport work [t km]
$w$	dosage [t ha <sup>-1</sup> ]
$R$	radius in the circular adjoining land [m]
$E$	distance from the storage location to the circle center [m]
$\Theta$	circular angle counter
$C$	correction factor for adjoining land

## Appendix

By assuming a circular area of adjoining land with a manure store positioned at a distance,  $E$ , from the center, the transport work may be estimated as:

$$T = 2 \times w \times \int_0^R \int_0^\pi \sqrt{(E + r \cos \Theta)^2 + (r \sin \Theta)^2} r dr d\Theta \quad (\text{A1})$$

where  $T$  is the transport work (t km),  $w$  is the dosage (t ha<sup>-1</sup>),  $R$  is the radius of the circular adjoining land (m),  $E$  is the distance from the storage location to the circle center (m), and  $\Theta$  is a circular angle counter. The assumption is that a uniform application rate is used throughout the whole area. By rearranging, the following is obtained:

$$T = 4 \times w \times \int_0^R (E + r) \times r \int_0^{\pi/2} \sqrt{1 - \frac{4Er \sin^2 \Theta}{(E + r)^2}} d\Theta dr \quad (\text{A2})$$

As the focus is to examine the dislocation of the storage from the center of the circular adjoining land, the following substitutions of  $E' = E/R$  and  $r' = r/R$  is introduced into Equation (A2) and using the principles of an elliptic integral of the second order, the following is obtained:

$$T = 2 \times w \times R^3 \times \pi \int_0^1 \frac{r'^3 + E' r' + E'^2 r'}{E' + r'} dr' \quad (\text{A3})$$

which may be abbreviated as:

$$T = 2 \times w \times R^3 \times \pi \times I(E') \quad (\text{A4})$$

where  $I(E')$  represent the integral in Equation (A3).

Two solutions are differentiated:

- 1)  $E' = 0$ , e.g., the storage is located in the center of the circle, then  $T = 2/3 \times w \times \pi \times R^3$ , where  $w \times \pi \times R^2$  expresses the total amount of manure being distributed on the adjoining land with an average transport distance of  $2/3 \times R$ .
- 2) For  $E \neq 0$ , e.g., the storage is located at a certain distance from the center. The integration of Equation (A3) is carried out using Simpson's numerical integration.