Simulation of Bin Loading Process During Manual Harvest of Specialty Crops Using the Machine Repair Model

Yiannis Ampatzidis[1], Stavros Vougioukas[2] and Matthew Whiting[3]

[1]Center for Precision and Automated Agricultural Systems, Washington State University, 99350 Prosser, WA, USA, e-mail: yiannis.ampatzidis@wsu.edu
[2] Department of Agricultural Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece, e-mail: bougis@agro.auth.gr
[3]Department of Horticulture and Landscape Architecture, Washington State University, 99350 Prosser, WA, USA, email: mdwhiting@wsu.edu

Abstract. Machine repair models play an important role in many applications including computer systems, maintenance operations, and manufacturing systems. In this paper the machine repair model was adapted to describe, analyze, and simulate an agricultural application: the bin loading process during manual harvest of two specialty crops – grapes in Greece and sweet cherries in USA. In addition, a management tool was developed in Matlab®, based on the proposed algorithm, to evaluate the performance of the system and find the optimal combination of bin "carriers" and "service stations". The use of repair models for agricultural operations shows promise for developing seasonable solutions for similar applications in other specialty crops (e.g. peach and apples).

Keywords: queueing systems, modeling, simulation, specialty crop harvest, machine repair model, finite source model.

1 Introduction

Specialty crops compete on most farms for limited capital, land, labor and management resources. These crops are characterized generally by high costs of production, heavy dependence upon manual labor, and high crop value. Harvest costs are often the single greatest expense for specialty crop producers. Harvest costs for sweet cherries (*Prunus avium* L.), for example, account for approximately 60% of total cost of production (Seavert et al., 2002, 2008). Fruit crops are also highly perishable and inefficiency in the harvest and handling process can have detrimental effects on product quality and storability. Proper management and optimization of

In: M. Salampasis, A. Matopoulos (eds.): Proceedings of the International Conference on Information and Communication Technologies
for Sustainable Agri-production and Environment (HAICTA 2011), Skiathos, 8-11 September, 2011.

harvest operations is essential for reducing costs and maintaining fruit quality. The window for harvesting fruit crops at optimum maturity varies by species but is generally considered to be a matter of days. Harvesting sweet cherries prematurely or beyond optimal timing affects consumer satisfaction with the fruit (Chauvin et al., 2009).

To optimize harvest efficiency the number of the machines and workers necessary for harvesting, handling, and transport, as well as the execution of field operations need to be planned. Recently, optimization algorithms for dynamic optimal planning of harvesting operations for agronomic crops (e.g. wheat, corn, and cotton) was introduced (Bochtis et al., 2006, 2007). The optimization criterion for planning the cooperation of a fleet of combines supported by a fleet of transport carts is the minimization of the total traveled length. Other optimization criteria include the minimization of the non-productive time, fuel consumption, in-field travel distance, and soil compaction in the field (Sørensena and Bochtis, 2010; Bochtis and Vougioukas, 2009; Bocthis et al., 2007b).

For specialty crops however, few simulation tools have been adopted successfully to improve work methods. Bechar et al. (2007) applied industrial engineering techniques to improve horticultural production in greenhouse tomato. They used two simulation models (Arena tool and an algorithm in Visual Basic) to compare alternative working methods in the trellising and harvesting stages and documented potential savings of up to 32% of manual labor. Guan et al. (2006, 2008) designed and formulated the farm work planning problem for geographically dispersed farms, based on the hybrid Petri nets, but they did not develop an optimization algorithm to improve farming process (farm work flow). Ampatzidis (2010) developed a simulation tool in Matlab, based in UML and hybrid Petri nets analysis, to calculate harvest efficiency during manual harvest of tree fruit in Greece. This algorithm does not optimize the harvest process but, an optimal solution can be achieved simulating a number of scenarios.

In this paper the bin loading process during manual harvest of specialty crop is modeled adopting a modified machine repair model (machine interference problem), from the operations research area. An algorithm was developed in Matlab®, based on the above model, in order to estimate the performance of the system (waiting time, expected number of worker/machines at the loading unit etc.) and improve confidence in sizing the fleet (workers and machines). Two different case studies are modeled using this algorithm: i) manual table grape harvest in Greece, and ii) sweet cherry harvest in Washington State, USA. First, the two different harvesting procedures are described. Then the machine repair model is formulated to model the harvest process. Finally, the bin loading process during grape harvest, in Greece, is simulated, as an example, and results are presented.

2 Harvesting Procedure

In this section, a brief description of the bin loading processes during manual harvest of grapes in Greece and sweet cherries in US are presented. Generally, the harvest process can be split into two discrete parts: α) picking fruit into bins (pick);

β) collecting the full fruit bins from the orchard (load) (Ampatzidis, 2010). The discrete part (α) is executed almost in the same way for both countries; only the capacity of the bins differs – 10 or 20 kg in Greece vs. ca. 170 kg in US. The procedure for loading differs however: in Greece, workers collect bins full of grapes using small hand-pushed carts whereas in USA, small tractors push a bin trailer able to collect up to 4 bins.

2.1 Manual Grape Harvest in Greece

Typically in Greece, manual grape harvesting is carried out with crews of 30 to 50 persons per field. There are typically two kinds of workers (Ampatzidis et al., 2008): the fruit pickers who harvest fruit from the vine, and the carriers who load filled bins onto small two-wheeled carts (Fig. 1) and manually transport them to a central collection point where the bins are loaded in trucks. The process is the following: grapes are harvested manually by fruit pickers and placed in vented plastic bins whose capacity is ca. 10 kg. Once filled, the bins are left on the ground next to the vine that was harvested. Next, the bins are loaded by the carriers into small carts (5-8 bins) which are transferred to a central location and loaded on a truck. After harvesting a field, the workers and their equipment are transported to another field which may or may not belong to the same farmer. When a truck is filled with bins it returns to the packinghouse; otherwise the truck's remaining free space is filled with bins from the next field.

Fig. 1. The "fruit pickers", who collect the grapes and the "carrier", who load bins into small hand-pushed cart.

2.2 Manual Sweet Cherries Harvest in WA

The general harvest process for sweet cherry fruit has not evolved in over a century. Pickers carry and place their ladder (2.75 to 4.5 m tall), climb to access fruit, place fruit into a metal bucket, whose capacity is limited by human carrying capability (7 kg), secured over their shoulders with straps. Fruit are harvested by grabbing pedicels and twisting, releasing them from the spur tissue. If the picking bucket is full, or all reachable fruit are harvested, pickers then climb down and dump fruit into a larger plastic or wood bin (capacity ca. 170 kg; 1.2 x 1.2 x 0.6 m), or continue to harvest until the bucket is filled. Next, the bins are collected, by a fleet of small tractors pushing hydraulic bin trailers that collect and transport up to 4 bins (referred to as "carriers", Fig. 2). Full bins are transferred to a central location and loaded on refrigerated trucks by forklift. Finally, they are delivered to local packing sheds for cooling, sorting, cleaning and packaging.

Fig. 2. Tractor pushes a bin trailer ("carriers") able to collect up to 4 bin.

3 Review of the Machine Repair Model

The machine repair (or machine interference, or finite-population, or machine-servicing etc.) model (MRM) is a finite source model, in which arrivals (or customers) are drawn from a small (finite) population (Winston, 2004). These systems consist of *K* machines subject to periodical breakdowns, and *S* repair persons. When a machine breaks down it is repaired by a crew of repair persons who therefore unavailable for repair other broken machines at the same time (Chen, 2006). Thus, the system performance (e.g. the expected number of broken machines, the expected time a machine spends waiting for repair, the time a particular repair person is idle) can be derived if key parameters of the system could be estimated, such as the breakdown and service rate. Also, the cost and profit analysis of the machine repair problem could be investigated (Ke and Wang, 1999; Armstrong, 2002; Schultz, 2004).

In a queuing system (*A*/*B*/*C*):(*D*/*E*/*F*), *A* denotes the arrival rate, *B* the service rate, *C* represents the number of the service stations, *D* states some general queue disciplines regarding the priority of serving (e.g. first-come, first-served, FCFS; last-come, first-served, LCFS; service in random order, SIRO), *E* denotes the maximum number of the customers allowed in the queuing system, and *F* states the size of the population that the customers are drawn. The finite model (*M*/*M*/*S*):(*GD*/*K*/*K*) denotes that the incoming traffic is modeled via a Poisson distribution (e.g. the machine breakdown rate (λ, inter-arrival rate) and service rate (μ) follow an exponential distribution (*M*)). The number of the machines is finite *K*, which can be repaired by a number of repair persons $S<K$. The queue discipline is first-come, first-served (FCFS). In this system arrivals are drawn from a small (finite) population *K*.

3.1 Adapting Machine Repair Model to Describe the Bin Loading Process

In this study the MRM was modified to model the bin loading process during manual harvest of two specialty crops (grape and sweet cherry). The “carriers” are treated as machine breakdowns and the trucks (or general the unloading points) are servers (repair persons) in the system. For example, in manual grape harvesting the “carriers” collect the bins (machine breakdowns) and move to the “unloading point”, where some other workers (one per truck - repair person), placed on the truck, unload and stack the bins into the truck.

Consider a MRM that consists of *K* “carriers” and *S* servers (unloading points), which work parallel and independent from each other. It is supposed the arrival rate (λ) of the “carriers” follows an exponential distribution (*M*). At any instant in time, a particular “carrier” either collects a bin in the orchard (outside the system), or unloads bins into the truck (waiting in queue or being served). When a “carrier” collects the bins (machine breaks down) and all the unloading station-servers are busy, it has to wait (Fig. 3). The first-come, first-served scheduling discipline is followed by the system, and hence when a server will be available, it will serve the first “carrier” in the line. Once a “carrier” is served (machine is repaired), it returns back to collect more bin (machine returns to good condition).

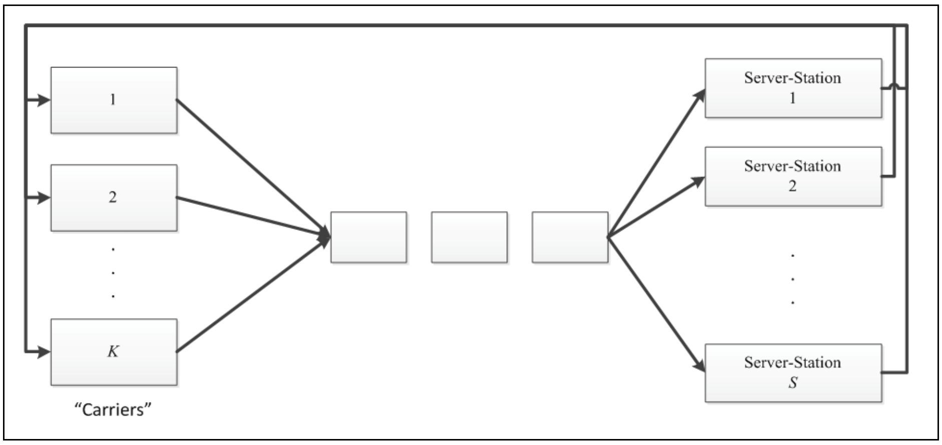

Fig. 3. A finite-source queuing model (machine repair model).

Further, the standard equations of the above queuing system are analyzed, using the theory of the birth-death processes and the limit theorems of probability theory (Sztrik and Bunday, 1993; Shashiashvili, 2007).

The steady state probability that there are n carriers (customers) in the queueing system will be given by equation:

$$P_n = \begin{cases} \binom{K}{n} \cdot \rho^n \cdot P_0 & 0 \le n < S \\ \binom{K}{n} \frac{n!}{S!} \cdot \frac{\rho^n}{S^{n-S}} \cdot P_0 & S \le n \le K \\ 0 & n > K \end{cases}, \text{ where } \binom{K}{n} = \frac{K!}{(K-n)! \cdot n!},\ \rho = \frac{\lambda}{\mu} \quad \textbf{(1)}$$

The probability of having zero carriers in the system P_0 is calculated by applying Little's queuing formulae $\sum_{n=0}^{K} P_n = 1$, where:

$$P_0 = \left[\sum_{n=0}^{S-1} \binom{K}{n} \cdot \rho^n + \sum_{n=S}^{K} \binom{K}{n} \cdot \frac{n! \cdot \rho^n}{S! \cdot S^{n-S}} \right]^{-1} \quad \textbf{(2)}$$

The expected average number of carrier waiting for service L_q (number of carries in the queue, queue length), the expected (average or mean) number of carries in the queuing system L (queue and service), and the expected (average or mean) number of carries receiving service L_S, when the system is in the steady state, can be calculated by equations:

$$L_q = \sum_{n=S}^{K} (n-S) P_n = L - S + P_0 \cdot \sum_{n=0}^{S-1} (S-n) \cdot \binom{K}{n} \cdot \rho^n \quad \textbf{(3)}$$

and

$$L = \sum_{n=0}^{K} n P_n = P_0 \left[\sum_{n=0}^{S-1} n \binom{K}{n} \rho^n + \frac{1}{S!} \sum_{n=S}^{K} n \binom{K}{n} \frac{n!}{S^{n-S}} \rho^n \right] \quad \textbf{(4)}$$

$$L_S = L - L_q \quad \textbf{(5)}$$

The average time a carrier spends in the queue W_q is calculated by:

$$W_q = \frac{L_q}{\lambda \cdot (K - L)} \quad \textbf{(6)}$$

The expected average waiting time in the system:

$$W = \frac{L}{\lambda \cdot (K - L)} \qquad (7)$$

Let E be the percentage of time that a carrier spends working outside the queuing system (carriers collect bins):

$$E = \frac{1/\lambda}{1/\lambda + W_q + 1/\mu} \qquad (8)$$

Also, if A is the average number of carries working outside the queuing system (collecting bins):

$$A = K \cdot E = K \frac{1/\lambda}{1/\lambda + W_q + 1/\mu} \qquad (9)$$

Finally, a management tool was created, utilizing the above equations, in Matlab R2009a, in order to estimate the performance of the system.

Below, the performance of a bin loading system was evaluated (number of carriers-servers, waiting time etc.), using the proposed algorithm, during the yield measurement and identification of grapes in a small vineyard in Greece.

3.2 Experimental Design

In this paper, bin loading systems are simulated, based on real measurements in the field, using a standard number of carriers and different number of service station (trucks). The performance of each system is evaluated.

At any instant in time, a particular carrier is in either "collecting bin from the field" or "unloading bins onto the trucks" condition. When a carrier arrives at a moment that all service stations are busy, it has to wait the carriers being served. Once a carrier is served, it returns to collect more bins. Hence, the parameters: arrival rate λ, and service rate μ, must be calculated, as they are used as "inputs" in the algorithm. Also, it must be investigated if these parameters follow an exponential (Poisson) distribution or some other distribution.

The arrival and service rates were calculated during loading and reckoning of the bin weight and ID in a small vineyard (size ~500 m^2), located at Folia Kavalas, in Northern Greece (Ampatzidis et al., 2008). In this experiment, a portable identification and weighing unit (PIWU, Fig. 4a) was mounted on the truck and hence each bin was identified and weighed as it entered the truck (Fig. 4b). In this queuing system the PIWU (and the trunk) treated as the servers and the carriers as the customers. Then, a number of carrier K=10 was selected and the system performance was evaluated under different number of the service stations (trunks with PIWU) S=1-4.

a b

Fig. 4. a) A portable identification and weighing unit (PIWU), with barcode reader and digital scale, b) Each bin can be identified and weighed as it enters the truck (Ampatzidis et al., 2008).

4 Results and Discussion

The carriers' arrival rate, as well as the service rate, followed a Poisson distribution, applying the Pearson's chi-square test (χ^2, test of goodness of fit, which establishes whether or not an observed frequency distribution differs from a normal distribution). Further, the average service rate was calculated as μ=1.6 carriers/min and the carriers arrival rate as λ=0.18 carriers/min. Also, because the ratio $\rho = \lambda / \mu = 0.1125 < 1$ the system is in equilibrium, has the Markov property and is ergodic, so that it has a unique equilibrium status and the equations 1-9 can be used. Using the proposed algorithm the manager of the farm can know the expected number of carriers in the queuing system, the expected number of carriers waiting for service, the expected average time a carrier spends in the queue or in the system etc.

Table 1 presents the system performance under different number of service stations (1 to 4), using the equations (and the algorithm) 1-9. It is observed, that using two service stations (trucks) the characteristics of system are improved satisfactorily and hence, two service stations (trucks) can be chosen for this system (ten carriers).

Table 1: Queuing systems characteristics. The service stations vary between 1 to 4.

System Characteristics \ Service Station #	**S=1, K=10**	**S=2, K=10**	**S=3, K=10**	**S=4, K=10**
P_o	0.171	*0.330*	0.349	0.351
P(1)	0.189	*0.364*	0.385	0.387
P(2)	0.187	*0.181*	0.191	0.192
P(3)	0.165	*0.080*	0.056	0.056
P(4)	0.127	*0.031*	0.014	0.011
L_q (carriers)	1.654	*0.187*	0.023	0.002
L (carriers)	2.482	*1.161*	1.014	0.995
W_q (min)	1.247	*0.120*	0.015	0.002
W (min)	1.872	*0.745*	0.640	0.627
E	0.752	*0.884*	0.899	0.901
A (carriers)	7.518	*8.893*	8.99	9.005

5 Conclusion

A paradigm for the planning and evaluation of a bin loading operation executed by bin carriers and transport trucks was presented in this paper. In this paradigm a mathematical modeling and optimization tool, from operation research, was adapted to model a common agricultural process for specialty crops. Further, a management tool was developed to evaluate this procedure. Using the proposed method and software, farm managers could investigate the performance of a bin loading system (e.g. the time a carrier or a service station –truck- is idle etc.) and choose the appropriate number of worker and machines for each orchard. Differenced harvest process for two specialty crops, grapes in Greece and sweet cherries in USA, can efficiently planning using the above model.

This algorithm could be used as a part of a general simulation tool which utilizes operation research techniques and optimization algorithms in order to model and improve the total harvest process and minimize the probability a worker or machine will be idle for a long period of time. Overall, the execution of harvest operations with a crew of workers and a fleet of machines must careful planned in order to collect, pack and distribute for sale, fruit with optimal quality and in the proper time.

References

1. Ampatzidis, Y.G. (2010) Ανάπτυξη μοντέλων χειρωνακτικής συλλογής οπωροκηπευτικών και τεχνικών αυτόματης καταγραφής δεδομένων για εφαρμογές γεωργίας ακριβείας και ιχνηλασιμότητας (Modeling and electronic

monitoring of activities during manual harvested of specialty crops with application to precision farming and traceability). PhD thesis (in Greek), Aristotle University of Thessaloniki 2010, Greece.

2. Ampatzidis, Y., Tzelepis, G. and Vougioukas, S. (2008) A low-cost identification system for yield mapping during manual vine harvesting. In: Proceedings of the International Conference on Agricultural Engineering & Industry Exhibition (AgEng 2008), Hersonissos (Crete), Greece, 23-25 June.
3. Armstrong, M.J. (2002). Age repair policies for the machine repair problem. European Journal of operation Research, 138 (2002), pp. 127-141.
4. Bechar, A., Yosef, S., Netanyahu, S. and Edan, Y. (2007) Improvement of work method in tomato greenhouses using simulation. Transactions of the ASABE, American Society of Agricultural and Biological Engineers, vol. 50(2): 331−338.
5. Bochtis, D.D. and Vougioukas, S.G. (2009) Minimising the non-working distance travelled by machines operating in a headland field pattern. Biosystems Engineering, volume 101, issue 1, September 2008, pages 1-12.
6. Bochtis, D., Vougioukas, S., Ampatzidis, Y., and Tsatsarelis, C. (2007a). Field Operation Planning for Agricultural Vehicles: A Hierarchical Modeling Framework. Agricultural Engineering International: the CIGR Journal of Scientific Research and Development, Manuscript PM 06 021. Vol. IX. February, 2007.
7. Bochtis, D., Vougioukas, S., Tsatsarelis, C., and Ampatzidis Y. (2007b) Optimal Dynamic Motion Sequence Generation for Multiple Harvesters. Agricultural Engineering International: the CIGR Journal of Scientific Research and Development, Manuscript ATOE 07 001. Vol. IX. July, 2007.
8. Bochtis, D., Vougioukas, S., Tsatsarelis, C. and Ampatzidis, Y. (2006) System Architectures for Dynamic Planning and Coordination of Machines Performing Agricultural Operations. In: Proceedings of the International Conference HAICTA (Information Systems in Sustainable Agriculture, Agroenvironment and Food Technology), Volos, Greece (September 20-23, 2006).
9. Chauvin, M.A., Whiting, M.D., and Ross, C.F. (2009) The influence of harvest time on sensory properties and consumer acceptance of sweet cherries. HortTechnol. 19:748-754.
10. Guan, S., Nakamura, M., Shikanai, T. and Okazaki, T. (2008) Hybrid Petri nets modeling for farm work flow. Computers and Electronics in Agriculture, 62, pp. 149-158.
11. Chen, Shih-Pin (2006) A mathematical programming approach to the machine interference problem with fuzzy parameters. Applied Mathematics and Computation, 174 (2006), pp. 374-387.
12. Guan, S., Matsuda, H., Shikanai, T. and Nakamura, M. (2006) Petri nets modeling and scheduling for farm work planning. In: Proceedings of the International Technical Conference on Circuits/Systems, Computers and Communications, vol. II, pp. 465–468.

13. Ke, J.C. and Wang, K.H. (1999) Cost analysis of the M/M/R machine repair problem with balking, reneging, and server breakdowns. Journal of the Operational Research Society, 50 (1999), pp. 275-282.

14. Schultz, C.R. (2004) Spare parts inventory and cycle time reduction. International Journal of Production Research, 42 (2004), pp. 759-776.

15. Shashiashvili, M. (2007) Cost minimization in Economics: maintenance of machines by a team of repairman (machine interference problem). Math Track. Vol. 3(2007), pp. 52-55.

16. Sørensen, C.G. and Bochtis, D.D. (2010) Conceptual model of fleet management in agriculture. Biosystems Engineering, volume 105, issue 1, January 2010, pages 41-50.

17. Sztrik, J. and Bunday, B.D. (1993) Machine interference problem with a random environment. European Journal of Operational Research, 65(1993), pp. 259-269, North-Holland.

18. Winston, W.L. (2004) Operations Research: Applications and Algorithms. 4th Edition, pp. 1104-1165, ISBN 0-534-38058-1. Indiana University, Brooks Cole.